Strong electromagnetic pulses generated in laser-matter interactions with 10TW-class fs laser

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Abstract. The results of an experiment on the generation of electromagnetic pulses (EMP) in the interaction of 10TW fs pulses with thick (mm scale) and thin foil (μm scale) targets are described. Such pulses, with frequencies in the GHz range, may pose a threat to safe and reliable operation of high-power, high-intensity laser facilities. The main point of the experiment is to investigate the fine temporal structure of such pulses using an oscilloscope capable of measurements at very high sampling rate. It is found that the amazing reproducibility of such pulses is confirmed at this high sampling rate. Furthermore, the differences between the EMP signals generated from thick and thin foil targets are clearly seen, which indicates that besides electric polarization of the target and the target neutralization current there may be other factors essential for the EMP emission.

1 Introduction

The problem of strong electromagnetic pulses in the frequency range from tens of MHz to several GHz emitted as a result of laser-target interaction has a long history [1-6], but a complete quantitative understanding of this effect is still lacking. Such pulses strongly interfere with the data acquisition systems and may pose a threat to safe and reliable operation of high-power, high-intensity laser facilities, so it is no wonder that mechanisms for their generation continue to attract attention [7-14]. In particular, in a series of recent articles [7-9] attention was given to the phenomenon of electric polarization of the target as a result of laser-target interaction, and the effect of EMP generation via the target neutralization current. Investigations reported in [7,8] utilized a specific form of the target called “lollipop” - which facilitated measurement of the target neutralization current and determination of the target charge - and they focused on thick (mm scale) targets. This analysis was recently extended [15] to thin (μm scale) foils, which are commonly used in laser-ion acceleration experiments; a dedicated experiment devoted to this issue was performed at the Eclipse laser facility in CELIA.

In [15] two characteristic effects observed in an experiment were noticed: (1) the patterns of EMP emitted for various laser pulse energies and pulse durations appear to be reproducible to an astonishing degree, despite the appearance of EMP as a random and chaotic phenomenon; (2) the patterns of EMP registered for thick and thin targets were somewhat different; they were dominated by the 1 ns-scale pulsation of the neutralization current, but displayed a sub-ns structure, which is indicative of a deviation from the simple picture of the target acting as an antenna and EMP originating primarily as a result of electric polarization of the target and the neutralization current. However, the characteristic patterns observed at the sub-ns time scale were recorded at the limit of the oscilloscope sampling rate, so one could suspect that their appearance would change once the measurement of EMP would be performed with better temporal resolution. In order to explore this issue we looked into the data collected in a brief experimental campaign consisting of 25 shots on the 10 TW fs laser facility at IPPLM in the end of 2016, when we had the rare opportunity to use a very high bandwidth oscilloscope. In this note we report briefly on the results of this campaign.

2 The experimental setup

The high-power laser facility in IPPLM is a Ti:Sapphire laser delivering an s-polarized beam with 810 nm central wavelength [16]. The beam is focused by an off-axis parabolic mirror to a spot approximately 20 μm in diameter. The beam was incident on the target at the angle of approximately 5º. The pulse duration was kept at 50 fs, and the pulse energy was varied in the range of 140 mJ to 270 mJ. The ns contrast was better than 10^{-8}. Similarly as in the case of the Eclipse experiment [15] the targets we used were placed in a “lollipop” target holder which consisted of a brass ring 14.0 mm in diameter, supported on a thin brass wire stalk - which in our case extended 12.0 mm above the standard target mount, i.e a distance was much shorter than in the case of the Eclipse experiment [15]. Here we report on two types of targets: (a) a massive Cu “pill” 10.1 mm in diameter and 1.0 mm thick; (b) an Al foil 6.0 μm thick,

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with a 0.3 μm layer of polystyrene on the rear side, pasted on the rear side of a Cu pill with ten 1 mm holes for shots (denoted further as AlPs target). However, there was no arrangement to measure the target neutralization current, and there was no grounded plate to ensure the mirror charge and dipole character of the radiation pattern as in the experiments on the Eclipse laser [7,8,15].

In order to measure the magnetic field we used a Prodyn B24(R) B-dot probe with an average equivalent area of ~9×10^{-6} m^2, which was placed at a point located 7.3 cm above the target, 25.0 cm behind the target and 7.0 cm to the right relative to the incident beam direction. The probe was oriented so as to measure the tangential component (relative to the vertical axis defined by the target stalk) of the magnetic field. The probe was connected through a Prodyn BIB-100G balun[a] and 2.53 m long RG400 Pasternack coaxial cable to the Keysight MSOV334A oscilloscope with a 16 GHz bandwidth.

3 Experimental results

In order to determine the physical value of the tangential component of the magnetic field B_{tg} the following procedure was used: (a) the raw signal for $\mathrm{d}B_{tg}/\mathrm{d}t$ was corrected for the 8 dB attenuation introduced by the balun; (b) a high pass Fourier transform (FT) filter was applied with the 180 MHz lower cutoff, determined empirically to reproduce null signal before the arrival of the main electromagnetic pulse; (c) a low pass FT filter was applied with a 10 GHz cutoff reflecting the location of the 3 dB point of the balun; (d) the correction was applied to take into account the frequency-dependent attenuation of the coaxial cable; (e) the inverse FT was performed to obtain the corrected and regularized data for $\mathrm{d}B_{tg}/\mathrm{d}t$; (f) the B_{tg} was obtained as a function of time by direct integration of $\mathrm{d}B_{tg}/\mathrm{d}t$. The overall B_{tg} signal has a well-known form a sequence of initial spikes followed by gradually decaying oscillations lasting approximately 200 ns. However, it is the first few ns of the signal that are most interesting, because that part originates directly from the target and is a direct reflection of the laser-target interaction; the signal at later times is a superposition of fields from various sources, including reflections of the original pulse from the chamber walls and equipment inside the chamber, and excitations of the chamber eigenmode oscillations. The B_{tg} obtained with the thick Cu target is illustrated in the Fig. 1, where two pulses recorded at different laser energies are compared as a representation of a broader sample. This figure is a good illustration for the astonishing reproducibility of the EMP patterns, which is fully confirmed in our study at a higher oscilloscope sampling rate.

In Fig. 2 we show the B_{tg} obtained with the thin AlPs target, where again two representative pulses recorded at different laser energies are displayed as an illustration for a broader sample. Also in the case of thin targets we find the pulse shape to be amazingly reproducible. Furthermore, we see that the pulses have a pronounced sub-ns structure which is different for thick and thin targets considered in our study. This is interesting, because our thin foil target support was designed so as to minimize electromagnetic differences between the thin foil and thick target setups. The case of a thin foil target may differ from a thick target by the fact that at the same laser pulse energy and duration one may expect somewhat larger electric charge to be generated on the target [15], but this is by itself is not sufficient to explain qualitative differences between EMP signal in those two cases. This indicates that in the setup we used the target charge and the neutralization current are not the only factors affecting the shape of the EMP signal.

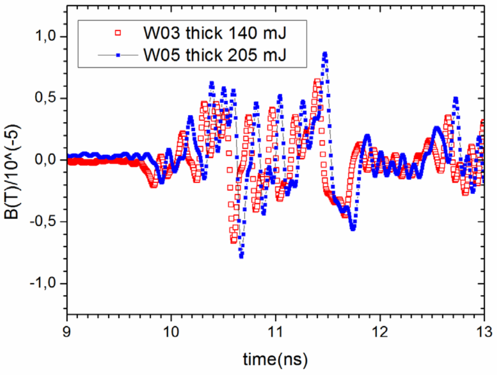

Fig. 1. The tangential component of the magnetic field as a function of time, as obtained in shots at the thick Cu target at two values of the laser pulse energy. Only the initial evolution of the pulse is shown, the total extent of the EMP signal is of the order of 200 ns.

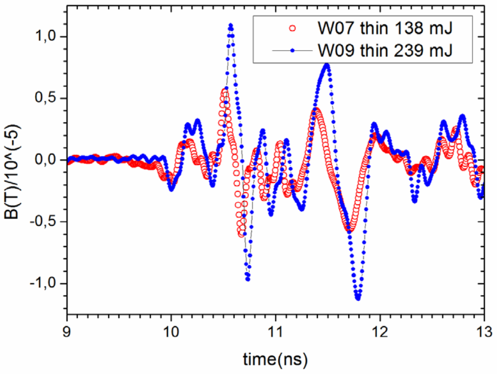

Fig. 2. The tangential component of the magnetic field, as obtained in shots at the thin foil AlPs target at two laser pulse energies.

For a further comparison of thin and thick targets we show in Fig. 3 a Fourier transform of a small part of the total signal, encompassing only the first 4 ns of the signal. We see that there are qualitative differences between these transforms: the short-time transform of the thin foil signal has a broad peak in the 1-2 GHz region and another one near 3.5 GHz, whereas the transform for the thick target is less pronounced in the 1-

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[a] https://ppmtest.com/products/baluns/prodyn-baluns/bib-series/

2 GHz region, but shows a peak near 4.5 GHz. Both spectra show some structure at the top of the range.

4 Conclusions

On the basis of our short study we may say that the amazing reproducibility of the EMP signals from shot to shot is fully confirmed at high oscilloscope sampling rate. We may also say that the presence of a sub-ns/multi-GHz component in the EMP signals is unlikely to be an oscilloscope artefact. Furthermore, we see that despite general similarities between EMP signals generated from thin foil and thick targets there are also clear differences, related to the multi-GHz component, indicative of the presence of EMP generation mechanisms beyond simple target polarization and neutralization current flow. We hope to further clarify these points in forthcoming experiments. In particular, it would be important to perform EMP measurements using electromagnetic probes sensitive to frequencies above 10 GHz.

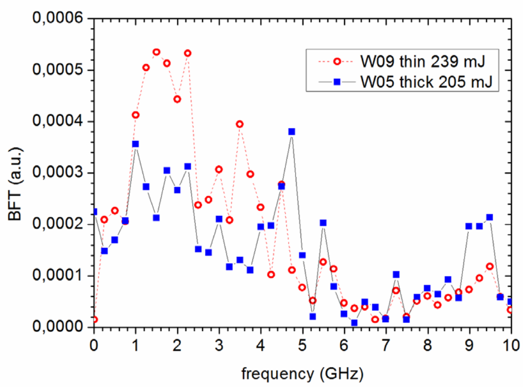

Fig. 3. The one-sided discrete Fourier transform spectrum of the first 4 ns of the EMP pulse generated from the thick Cu target (W05) and the thin AlPs target (W09).

The experiment on which we report here was closely modelled on the experiment devoted to EMP from thin targets at Eclipse facility [15], which was done in collaboration with J.-L. Dubois, S. Hulin, and V. Tikhonchuk (CELIA), to whom the present authors are greatly indebted. We are also grateful to D. Neely (RAL) for lending us the Prodyn B24 B-dot probe. We want to express our gratitude to the company AM Technologies (Warsaw) and in particular to their representative T. Szabłowski for giving as access to a 16 GHz oscilloscope. This research is supported by the Polish National Science Centre grant Harmonia 2014/14/M/ST7/00024. Our collaboration has profited greatly from the intellectual environment created by the COST Action MP1208.

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