Measurements of electromagnetic pulses generated from ultra-thin targets at Vulcan Petawatt

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Introduction

One of the effects accompanying the laser-target interaction at high laser intensities is the generation of strong electromagnetic pulses (EMP) with frequencies in the range of tens of MHz to few GHz [1]. Such pulses may interfere with the electronics of the data acquisition systems and pose a threat to the safe and reliable operation of high-intensity laser facilities, it is therefore important to characterize them for various laser and target conditions and to develop a predictive model. A dedicated effort was made to this end [2-7], but it seems that definite quantitative understanding of the EMP phenomenon has not been achieved, and this subject continues to attract interest [8-15]. Recent investigations have shown that besides being an issue of considerable practical importance the EMP effect is also a challenging scientific problem.

In this note we briefly report on EMP measurements performed at Vulcan as a ride-along investigation during an experiment devoted to the study of laser interaction with ultra-thin (10's to 100's nm) targets. Such targets undergo substantial deformation during the interaction, with the possibility of forming particle jets, resulting in conditions for which EMP generation had been rarely studied so far. Furthermore, proper conditions were created to capture the multi-GHz component of the resulting electromagnetic pulses.

Experimental setup

The laser and target arrangements were typical for a Vulcan experiment on laser-driven ion acceleration in Target Area Petawatt, with a plasma mirror redirecting the beam at 30º angle to the target normal. Targets were supported on plastic stalks to suppress emission of EMP [15]. Both the magnetic and electric fields were measured using conductive B-dot and D-dot probes. Electromagnetic probes were placed on dielectric supports to minimize the disturbance to the measured fields. High-bandwidth double-shielded 11.0-13.5 m long RG400 coaxial cables were used to connect the probes to a LeCroy Wavemaster 813Zi-B oscilloscope with a 13 GHz bandwidth and 4×40 GSa/s sampling rate. The oscilloscope was enclosed in a Faraday cage to protect it from picking up any electromagnetic disturbances propagating directly through the air. It was triggered by external trigger signal picked up from the main beam.

Measurements of the magnetic field

The measurement of the magnetic field was done with a Prodyn B24 B-dot probe and a Moebius loop. We report here only the result from the B-dot probe. The probe was placed on the laser side of the target 40 cm from the target, 19 cm above the target, in a vertical plane inclined approximately 48º to the target normal. The orientation of the probe was such that it was sensitive to the tangential component of the magnetic field relative to a vertical axis passing through the target. The probe was connected to the Prodyn BIB-100G balun that provided unbalanced output. To obtain the value of B as a function of time the raw signal was corrected for 8 dB attenuation introduced by the balun, as well as any external attenuation at the oscilloscope terminal (typically 6 dB), then a low pass 9 GHz filter was applied to limit the frequencies to the 3 dB range of the probe, and finally a frequency-dependent attenuation introduced by the coaxial cable itself was taken into account. This latter correction is quite important, given the fact that the cable attenuation is an increasing function of the frequency, reaching 0.6 dB/m at 1 GHz and 1.1 dB/m at 3 GHz. The resulting expression for d*B*/d*t* was then integrated numerically to obtain *B(t)*. In Fig. 1 we show *B(t)* recorded for a shot employing a 65 nm CH target with 152 J on a target and 1100 fs duration, which is representative of a broader sample. The signal consists of a narrow initial spike with the amplitude of ~2×10^{-4} T, followed by a decay lasting somewhat more than 200 ns.

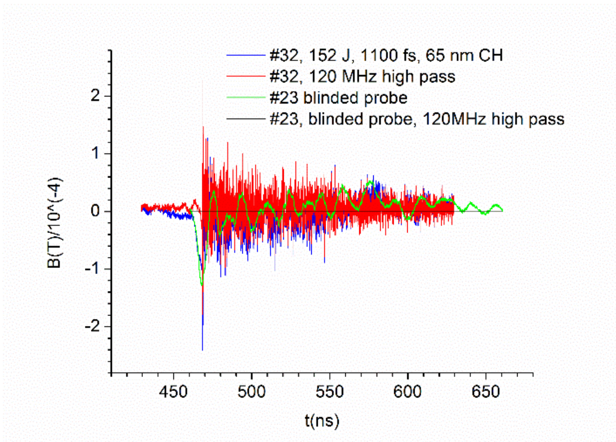

Figure 1. The tangential component of the magnetic field induction *B* as a function of time *t*, as recorded with a B-dot probe inside the chamber after a shot on a 65 nm CH target with 152 J on target, with 1100 fs duration (blue), compared with the signal from a blinded probe, measured under similar laser and target conditions (green). The signals obtained after applying 120 MHz high pass filter are also shown (red and black, respectively).

In EMP measurements the question of signal-to-noise ratio is of utmost importance, and to illustrate this issue we show in Fig. 1

the signal recorded for a shot with similar parameters with the B-dot probe blinded by several layers of Al foil. We find that our setup indeed records some signal when the probe is blinded, but the spectrum of this signal is below 120 MHz. Applying 120 MHz high pass filter to this signal gives almost a null result, which means that for frequencies higher than 120 MHz the signal-to-noise ratio is excellent. Concerning the part of the signal of the blinded probe below 120 MHz it has yet to be clarified whether this is a manifestation of limitations of the shielding we applied or it has some genuine physical origin, such as the signal recorded by our setup independently of the B-dot probe itself (due perhaps to a direct interaction of particles and X-rays) or simply an artefact of the oscilloscope response to a narrow initial peak. In any case, applying the 120 MHz high pass filter to the signal from the unshielded probe we find that the resulting change is small, which shows that frequencies below 120 MHz carry only a small portion of the overall recorded signal.

In Fig. 2 we show the FFT spectrum of the signal presented in Fig. 1. We see a broad distribution with significant contributions from the multi-GHz region. For comparison we also show the spectrum of the signal from the blinded probe, which shows that above, say, 400 MHz the signal-to-noise ratio becomes excellent.

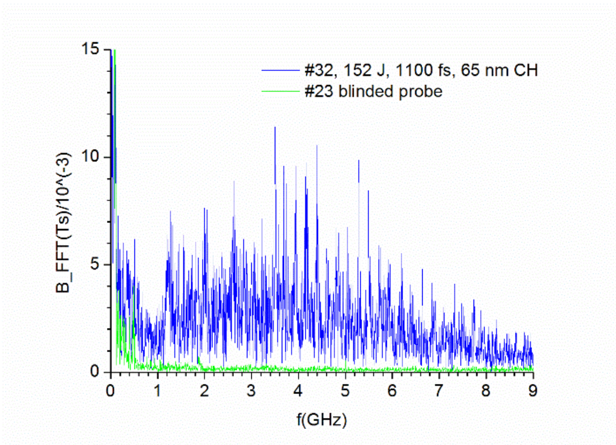

Figure 2. The spectrum of the magnetic field signal shown in Fig. 1, compared with the spectrum of the signal obtained with a blinded B-dot probe.

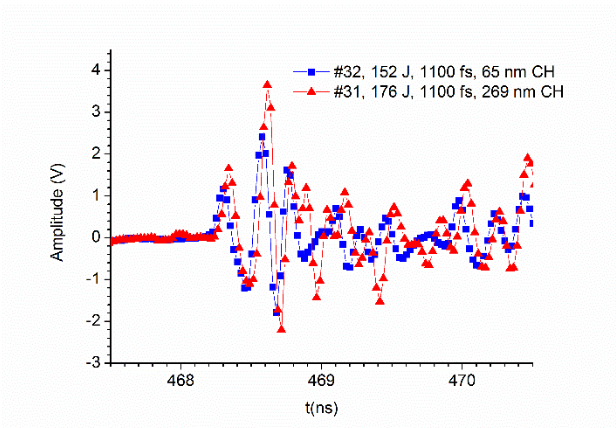

Figure 3. Comparison of the amplitude of the signal from the B-dot probe, corrected only for the attenuation at the oscilloscope terminal, for two shots employing CH targets, shown at fine time resolution, illustrating surprising reproducibility of the EMP field evolution from shot to shot.

The electromagnetic signals resulting from laser-solid interactions appear at first glance as random and chaotic and are generally regarded as "noise". It is thus interesting to note that in fact they are reproducible from shot to shot to a surprising degree, having similar appearance over a range of energies and pulse durations, as was first pointed out in [14] for signals obtained with a laser system giving 100 mJ laser energy on target. It turns out that the same effect is found in our investigation. To illustrate this we compare in Fig. 3 the raw signal (corrected only for the external attenuation at the oscilloscope terminal) for two shots with similar laser parameter and targets differing in thickness, shown at a very fine time scale. We see that these signals are well resolved with the sampling rate that was used, and that they are indeed remarkably similar in appearance, apart from a difference in the overall amplitude. This suggests that there is some well-defined mechanism behind the EMP generation.

Measurements of the electric field

The measurement of the electric field intensity was performed with up to three Prodyn FD-5C probes. Here we show results of the measurement done with a probe placed just outside of the chamber at the same height as the target, at distance of 1 m from the target, in the center of a glass window 250 mm in diameter and 30 mm thick, with the line of sight to the rear of the target at an angle of approximately 27º from the target normal. The procedure of extracting *E(t)* from the oscilloscope signal is the same as in the case of *B(t)*. In Fig. 4 we show *E(t)* recorded for the same shot as in Fig. 1.

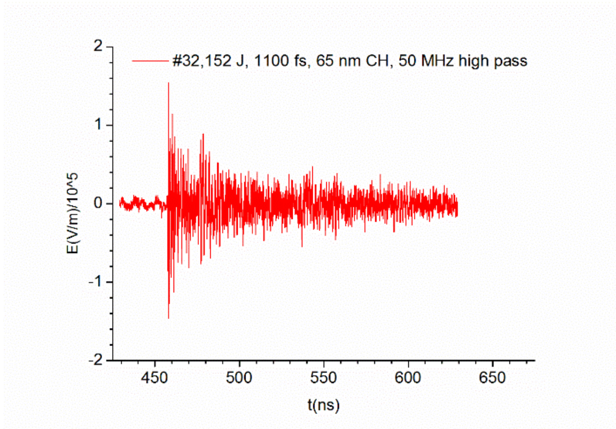

Figure 4. The vertical component of the electric field intensity *E* as a function of time *t*, recorded with a D-dot probe placed outside of the chamber in a glass window for the same shot as in Fig. 1. A 50 MHz high pass filter was applied..

Similarly as in the case of *B(t)* the contribution of low frequency part of the spectrum to the overall signal is small and is filtered out by applying a 50 MHz high pass filter, which has only a small effect. The initial spike has the magnitude on the order of 150 kV/m. In Fig. 5 we show the FFT spectrum of the signal presented in Fig. 4, in which an important contribution from the multi-GHz region may be clearly seen.

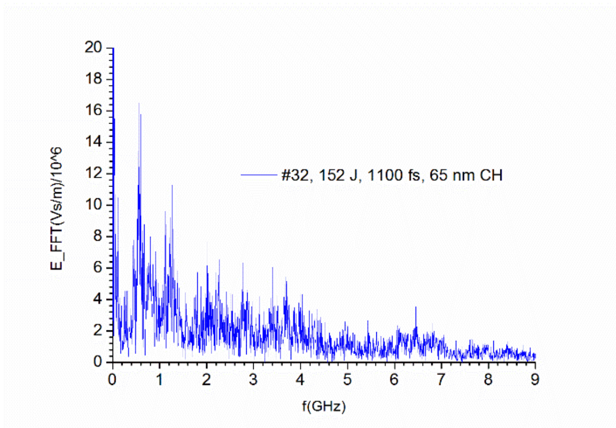

Figure 5. The spectrum of the electric field signal shown in Fig. 4.

Our result is of the same order of magnitude as that reported in [7] for the case of the Titan laser, at similar laser parameters. On the other hand, it is an order of magnitude higher than results reported in [11] for the Vulcan laser. The reason for discrepancy with [11] is rather clear: authors of [11] concentrate on the frequency range extending to 250 MHz, consistent with the bandwidth of their optical probe; they do report seeing a high-frequency signal approximately between 0.8 and 1.2 GHz, but they treat it as a noise and filter it out using a low pass filter before further processing. If this high-frequency contribution had been retained and the frequency-dependent cable attenuation correction – which may be quite large for higher frequencies – had been taken into account, it is quite likely that a significantly higher value of the signal would have been obtained.

Conclusions

Measurements of the EMP generated at Vulcan Petawatt from ultra-thin targets have been performed using conductive B-dot and D-dot probes. It was found that the spectrum of these pulses is quite wide and the multi-GHz component constitutes the bulk of the signal. It was also found that despite having a random and chaotic appearance such pulses are reproducible from shot to shot to a surprising degree. Electric fields on the order of 150 kV/m were measured behind a glass window just outside the experimental chamber.

Acknowledgements

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