Acceleration, transport and dephasing of electrons in dense plasmas irradiated with Petawatt laser pulses

J Osterholz, R Jung, K Löwenbrück, S Kiselev, A Pukhov, G Pretzler, O Willi
Heinrich-Heine-University Düsseldorf, D-40225 Düsseldorf, Germany

S Kar, M Borghesi
Queen's University of Belfast, Belfast BT7 1NN, UK

W Nazarov
University of Dundee, Dundee, DD1 4HN, UK

S Karsch, R J Clarke, D Neely
Central Laser Facility, CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX, UK

Main contact email address: *osterhol@uni-duesseldorf.de*

Introduction

The acceleration and the transport of electrons in solid foil or foam targets irradiated with ultra-intense laser pulses have generated a significant interest in the recent years. These issues are relevant for laser based electron acceleration, for the fast ignitor scheme in inertial confinement fusion and for the development of ultra-fast X-ray sources. There are several mechanisms such as $j\times B$ heating, vacuum heating, resonance absorption or direct laser acceleration which contribute to the acceleration of the electrons. The temporal characteristics, i.e. bunching of the electrons depend on the experimental conditions and the predominant acceleration mechanism. For p-polarized laser pulses incident obliquely onto the target, vacuum heating and resonance absorption play important roles. Under these conditions, typically one bunch of electrons per laser cycle is generated. In contrast, if the laser pulses are incident perpendicular to the target surface, the acceleration is governed by ponderomotive $j\times B$ heating. In this case, two electron bunches per laser cycle are injected into the target. However, the situation is more complicated at ultra-high intensities when the shape of the critical surface is modified by the light pressure, which is the case for Petawatt laser pulses.

Direct experimental evidence of bunching of electrons accelerated in laser irradiated foil targets is reported in[1,2]. In these experiments, the optical transition radiation (OTR) was investigated which is emitted when the electrons cross the plasma-vacuum boundary at the target rear side. For a bunched electron beam, the contributions of the individual electrons add up coherently, leading to the emission of coherent transition radiation (CTR). The spectrum of CTR is peaked around the multiples of the bunching frequency. Thus the CRT spectrum contains important information about the predominant acceleration mechanism. For the interpretation of the CTR spectra, the transport of the electrons through the target plays an important role. Due to velocity dispersion, the duration of the electron bunches increases as they propagate through the target. This effect, schematically shown in Figure 1, is also referred to as electron dephasing. Consequently the CTR intensity is smaller for thick targets.

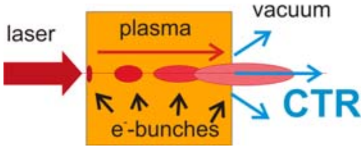

Figure 1. CTR emission from the rear side of laser irradiated targets. Velocity dispersion leads to an increase of the duration of the electron bunches during their propagation ("dephasing").

Here we report on an experiment investigating the CTR emission from foam targets irradiated with Petawatt laser pulses. In the experiment bunching and dephasing of the electrons is evident. From the measured data, the hot electron temperature is derived.

Experimental setup

The experiment was carried out at the Vulcan Petawatt laser facility at the Rutherford Appleton Laboratory. A schematic drawing of the setup is shown in Figure 2. The laser pulses with a wavelength of λ_0=1053 nm, an energy of 350 J and a duration of 750 fs were focused with an f/3.2 parabola. The focal spot with a diameter of 6 µm contained about 75% of the laser energy, resulting in a target intensity of $5\cdot10^{20}$ W/cm^2. The p-polarized laser beam was incident under an angle of 45°. The optical emission from the target rear side was imaged with an f/2 objective. The spectral composition of the emitted light was analyzed with a spectrometer in the wavelength range around 527 nm. The energy spectra of the electrons which were emitted in the direction of the laser were recorded with a permanent magnet electron spectrometer.

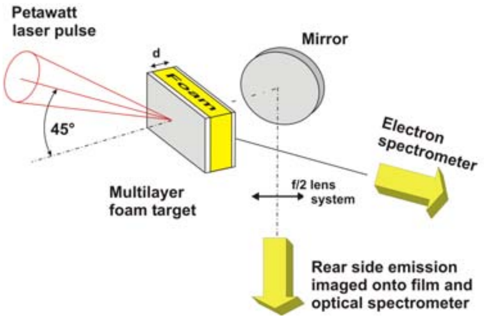

Figure 2. Schematic drawing of the experimental setup.

In the experiment, foam targets with different thicknesses (250, 500 and 750 µm) and densities (100 and 200 mg/cm^3) were used. The front sides of the targets were coated with a 75 nm gold layer. During the leading edge of the laser pulse a radiation wave with a temperature of about 150 eV was generated in the gold layer, leading to a pre-ionisation of the foam targets. Thus homogenous foam plasmas with electron densities between 15 and 30 times overcritical density were obtained. The rear sides of the foams were coated with a 200 nm aluminum layer. This was done in order to achieve a sharp plasma vacuum interface which is essential for the generation of optical transition radiation.

Results and discussion

Figure 3 shows the spectra of the light emitted from the rear side of foam targets with different thicknesses. For the 250 µm target, the emission is peaked around a wavelength of 527 nm with some broadband underground. It is expected that the broadband underground is due to (non-coherent) OTR, whereas the peak around 527 nm is the contribution of the CTR[3]. The peak in the spectrum clearly demonstrates that the electrons are bunched either at the laser frequency ω or at twice the laser frequency 2ω. For the 500 µm target, only a small peak is observed, whereas no peak is seen for the 750 µm target.

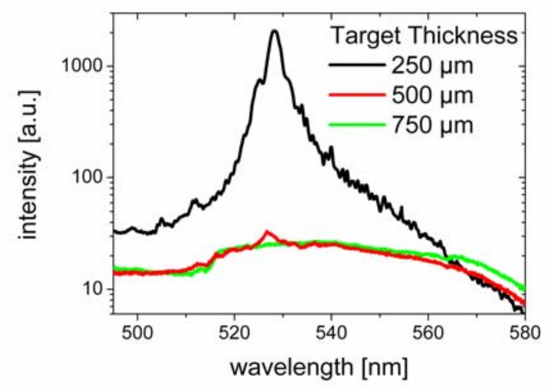

Figure 3. Spectra of the emission from the rear side of foam targets with different thicknesses. The decrease of the CTR intensity for the thick targets is attributed to dephasing of the electrons.

For the interpretation of the spectra, it is assumed that two electron bunches per laser cycle are accelerated in laser direction. This corresponds to the situation where the interaction is governed by $j \times B$ heating, which seems reasonable due to the high intensity of the Petawatt laser pulses[4)]. Bunching at 2ω was also confirmed in 3D PIC simulations calculating the acceleration of the electrons at the target front side for the conditions in the experiment (results not shown). For an angle of 45° to the target normal, the electron propagation length z in the target is larger than the target thickness by a factor $\sqrt{2}$.

The CTR emission from the target was calculated with a 1-dimensional ballistic transport model[1)]. In this model, a number of M electron bunches with a temporal delay δT, each containing P electrons, are injected into the target. The electrons have a 1D relativistic Maxwellian velocity distribution with a temperature T. Figure 4 shows the current at the target rear side calculated for the targets used in the experiment. Note that the plots for 707 µm and 1061 µm propagation length are shown with an offset for a better distinction. The parameters for the calculation are T=8MeV, M=426 (corresponding to the laser pulse length of 750 fs), and P=6.6·10^9 (corresponding to a total number of 2.8·10^{12} electrons). The effect of dephasing is clearly visible, as the modulation depth of the current decreases with increasing z.

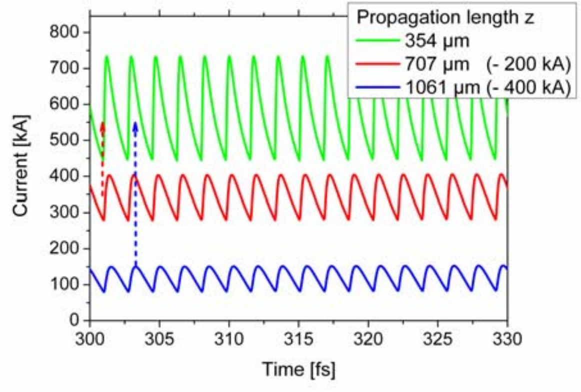

Figure 4. Current transported by the electron bunches for different propagation lengths. The plots for 707 µm and 1061 µm propagation length are shown with an offset for a better distinction.

For the CTR spectrum it is obtained [1]:

$$I_{CTR}(\omega)=\eta(\omega)P^2\left|j(\omega)\right|^2\frac{\sin^2(M\omega\delta T/2)}{\sin^2(\omega\delta T/2)} \qquad (1)$$

Here $\eta(\omega)$ is the light intensity at frequency ω emitted by a single electron into the aperture of the detector, $j(t)$ is the normalized flux corresponding to one single electron bunch at the target rear and $j(\omega)$ is its Fourier transform.

In Figure 5, the intensity of the CTR peaks at 2ω is calculated for different temperatures between 1 and 8 MeV. The intensity at a propagation length of 354 µm is normalized to 1. From the ratio of the CTR peaks of the 250 and the 500 µm target measured in the experiment, an electron temperature between 1 and 2 MeV was derived.

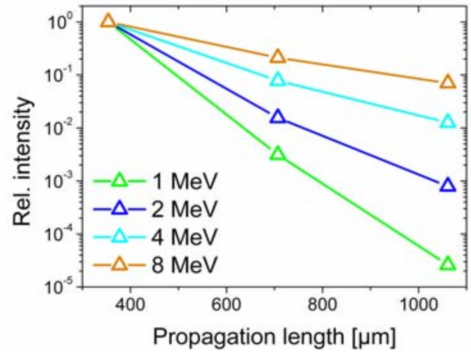

Figure 5. Intensity of the CTR for different electron temperatures and propagation lengths calculated with a ballistic transport model.

Besides the CTR diagnostic, the electron temperature was also measured with an electron spectrometer (see [5)], data not shown here). The electron spectra could be well described by a two temperature Boltzmann distribution with a "cold" temperature of 2 MeV and a "hot" temperature of 8 MeV. This is in contrast to the temperature determined with the CTR diagnostics. Either of the following points might explain this observation: (i) Only the "cold" electrons are bunched and contribute to the CTR emission, (ii) due to charge up effects the number of cold electrons is underestimated in the electron spectrometer, or (iii) the interaction of the electrons with the plasma cannot be neglected and the assumption of a ballistic transport does not hold in this experiment. Further PIC simulations are currently under progress to clarify this point.

Summary

In summary, we have investigated the acceleration and transport of electrons in foam targets irradiated with Petawatt laser pulses. In the experiment, the spectra of the CTR emitted from the target rear sides were observed. For thin targets the CTR emission is peaked around twice the laser frequency, clearly showing that the electrons are bunched. The CTR intensity decreases for the thicker targets, which is attributed to dephasing of the electrons as they propagate through the target.

Acknowledgements

This work was funded by the EU Large Facility Program and was performed within the SFB/Transregio TR 18. The excellent service of the RAL staff is acknowledged.

References

1. S D Baton *et al.*, Phys. Rev. Lett. 91, 105001 (2003)
2. J Zheng *et al.*, Phys. Rev. Lett 92, 165001 (2004)
3. J J Santos *et al.*, Phys. Rev. Lett. 89, 025001 (2002)
4. E L Clark *et al.*, Phys. Rev. Lett. 85, 1654 (2000)
5. R Jung *et al.*, Phys. Rev. Lett. 94, 195001 (2005)