Investigation of fast electron energy coupling in a counter-propagating scheme

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Abstract

A detailed knowledge of the physical phenomena underlying the transport of fast electrons generated in high-intensity laser-matter interactions is of fundamental importance for the fast ignition scheme for inertial confinement fusion. The fast electron currents largely exceed the Alfven limit, therefore a balancing return current is required to support the propagation of the fast electron beam in the target medium.

An experimental study aimed at investigating the role of the return current on the dynamics of the fast electron beam was carried out with the Vulcan Petawatt beam. Two counter-propagating electron beams were generated by double-sided irradiation of a layered target containing a 5 micron thick Ti layer. Information on the energy coupling of the fast electron beam to the Ti layer was retrieved through X-ray measurements. In particular, high-resolution X-ray spectroscopy of the Ti emission lines was performed in the spectral range from 4.4 to 5.1 keV including the Lyα, the Heα and the Kα line. Spectra were acquired for double-sided irradiation with different timings between the two laser beams as well as for single-sided irradiation.

The recorded spectra indicate a higher target temperature for a precise timing between the two beams in agreement with simulation results.

Introduction

In the context of the Fast Ignition approach to Inertial Confinement Fusion the understanding of the fast electron transport and energy deposition plays a crucial role [1]. In addition, the development of ultra-short X-ray sources [2] and the optimization of proton acceleration [3] during the interaction of high-intensity laser-interaction with solid target foils require a detailed knowledge of the fast electron dynamics.

In general, due to the huge fast electron currents generated in high-intensity laser-solid interactions the propagation of the electron beam is not simply determined by the collisions of the electrons with the target atoms [4]. Self-generated electric and magnetic fields can play a major role in the electron energy deposition [5] and should be included in the modelling of the experimental data. In particular, the onset of a balancing return current is required to support the propagation of the fast electron beam. Filamentation of the electron beam, as observed experimentally [6] and found in simulations [7] due to the interaction of the electron beam with its cold return current is currently under study with particular attention to the role of filamantation in the electron energy deposition.

The experiment presented here aims at investigating the role of the return current on the fast electron dynamics. Therefore, results from standard single-sided irradiation are compared with double-sided laser irradiation of a target foil. The energy deposition in the target material is measured through high-resolution X-ray spectroscopy.

The fast electron transport experiment in a counter-propagating scheme

The experiment was carried out using the VULCAN Petawatt beam with a pulse energy up to 400 J and a pulse duration of 700 fs at a wavelength of 1054 nm. The laser pulse was divided spatially into two beams. One half of the beam, beam 1, was sent to the main parabola and a second smaller beam, beam 2, was obtained by means of a pick-off mirror inserted in the second half of the laser beam. A delay-line on beam 2 allowed to vary the time delay between the two beams. The two beams were synchronized using an optical streak camera, thus resulting in a 1 ps uncertainty for the absolute value of the time delay. The role of the uncertainty on the data analysis is discussed below. The energy ratio of the two beams was found to be $E_2/E_1 \sim 1/4$ from chalorimetric measurements.

The two laser beams were focused on either side of the target foil consisting of a 5 μm thick Ti foil, either uncoated or coated on both sides with a 1 μm thick Al layer. Beam 1 was defocused in order to match the intensity of both beams and to ensure spatial overlapping of the generated fast electron beams in the target. The main diagnostics were two bent crystal X-ray spectrometers mounted on either side of the target foil and tuned to reflect the spectral range between 2.1 and 2.8 Å containing the Ti emission lines between the Kα and the Lyα line. The spectrometers were equipped with image plate detectors.

An example of the lineout of a recorded X-ray spectrum, obtained from the irradiation of an uncoated 5 μm thick Ti foil used for alignment of the diagnostics and line identification is shown in Fig. 1. In the graph emission lines from cold Ti atoms, from He-like Ti ions and from Li-like Ti ions can be identified. The cold Kα line is clearly visible on the long wavelength side (2.75 Å). At 2.62 Å the Heα line is visible and the broader and lower peak around 2.48 Å is due to transitions of the type 1s2p4l-1s^{2}3l' from Li-like ions [8].

Similar X-ray spectra were recorded from the irradiation of target foils consisting of a 5 μm thick Ti layer coated on either side with a 1 μm thick Al layer to avoid direct irradiation of the Ti layer with the laser light. The X-ray spectra were acquired for single-sided irradiation and double-sided irradiation with different time delays between the two laser beams. The relative intensities of the emission lines originating from the different ionization stages varied for different time delays as follows. In the case of a nominal time delay of 0 ps strong emission around 2.48 Å from Li-like ions was observed, but no emission from He-like ions and no Kα line emission was visible above the noise level. For a nominal time delay of +0.5 ps, which is of the order of the laser pulse duration, the spectrum shows emission from He-like ions and the intensity of the lines originating from Li-like ions is reduced. The Kα line is also present in the spectrum. For a nominal delay of +1 ps this trend is confirmed. In this case the intensity of the emission lines from He-like ions is higher than the intensity of the Li-like emission lines. Finally, in the case of single-sided irradiation with only beam 1, the spectrum shows the same features as the one obtained from double-sided irradiation with a nominal delay of 0 ps, that is strong emission from Li-like ions is observed and no emission from He-like Ti ions is visible in the spectrum.

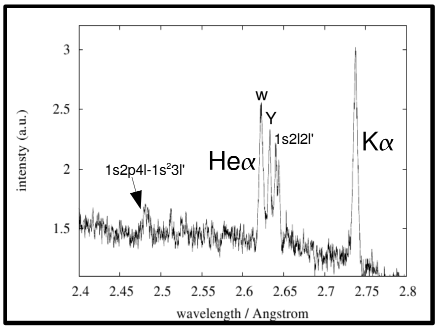

Figure 1: X-ray spectrum obtained from the irradiation of a 5 μm thick Ti foil.

Discussion

The experimental results presented in the previous section show that the ionization stage of the Ti layer changes from predominantly Li-like ions to He-like ions, when the delay between the two laser beams is varied by an amount of the order of the laser pulse duration. The characteristics of the X-ray spectrum obtained from single-sided irradiation are recovered for double-sided irradiation with a nominal time delay of 0 ps, indicating that the two generated fast electron beams do not interact significantly in this case. In fact, recalling that the synchronization of the laser beams was performed with an uncertainty of 1 ps, it can be concluded that the nominal delay of 1 ps most probably corresponds to a simultaneous irradiation of the target foil by the two driving laser beams.

The higher ionization stage of predominantly He-like ions in the case of simultaneous irradiation with the two laser beams indicate that a higher target temperature is reached when the counter-propagating fast electron beams interact. A similar rise of the target temperature was found in numerical simulations carried out with the LSP [9] code. Single-sided injection of a fast electron beam corresponding to an intensity of 10^{20} W/cm^2 was compared to double-sided injection maintaining the total injected energy constant. The simulation results at the end of the laser pulse show that in the case of single-sided injection the centre of the target reaches a temperature of about 400 eV whereas for counter-propagating electron beams the temperature rises to about 600 eV at the centre of the target.

In conclusion, the experimental results indicate that enhanced energy deposition is achieved for simultaneous double-sided irradiation of the target foil. Clearly, more investigation is needed to get a deeper insight in the physical phenomena involved in this scenario. In any case, the configuration based upon high-resolution X-ray spectroscopy of the emission in a scheme of counter-propagating fast electron beams seems to be very sensitive to anomalous energy deposition in the target foil.

References

[1] M. Tabak et al, Phys. Plasmas **1**, 1626 (1994)

[2] A. Rousse et al, Phys. Rev. E **50**, 2200 (1994)

[3] J. Fuchs et al, Nat Phys **2**, 48 (2006)

[4] D. Batani, Laser Part. Beams **20**, 321 (2002)

[5] O. Klimo, V. T. Tikhonchuk and A. Debayle, Phys. Rev. E **75**, 016403 (2007)

[6] M. Wei et al, Phys. Rev. E **70**, 056412 (2004)

[7] A. Karmakar et al, Phys. Rev. E **80**, 016401 (2009)

[8] J. Nilsen, Atomic Data and Nuclear Data Tables **38**, 339 (1988)

[9] D.R. Welch et al, Nucl. Instrum. Methods Phys. Res., Sect. A **464**, 134 (2001)