Measurement of Fast Electrons Spectra Generated by Interaction between Solid Target and Peta Watt Laser

T. Tanimoto, H. Habara, K. A. Tanaka, R. Kodama, M. Nakatsutsumi, K. L. Lancaster, J. S. Green, R. H. H. Scott, M. Sherlock, P. A. Norreys, R. G. Evans, M. G. Haines, J. King, T. Ma, M. S. Wei, T. Yabuuchi, F. N. Beg, M. H. Key, P. Nilson, R. B. Stephens, H. Azechi, K. Nagai, T. Norimatsu, K. Takeda, J. Valente, and J. R. Davies

1 Graduate School of Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan
2 Laboratoire pour l’Utilisation des Laser Intenses (LULI), CNRS, Ecole Polytechnique, Route de Saclay, 91128 Palaiseau, Cedex F 91128, France
3 STFC Rutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot, Oxfordshire OX11 0QX, United Kingdom
4 Department of Physics, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2BZ, United Kingdom
5 Centre for Plasma Physics, School of Mathematics and Physics, Queens University Belfast, University Road, Belfast BT7 1NN, United Kingdom
6 Department of Mechanical and Aerospace Engineering, UC San Diego, 9500 Gillman Drive 0411, La Jolla, California 92093-0411, United States of America
7 Lawrence Livermore National Laboratory, P.O.Box 808, Livermore, California 94550, United States of America
8 Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, New York 14623, United States of America
9 General Atomics Corp. PO Box 86508, San Diego, California 92186-5608, United States of America
10 Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan
Abstract. Fast electron energy spectra have been measured for a range of intensities between $10^{18}$ Wcm$^{-2}$ and $10^{21}$ Wcm$^{-2}$ and for different target materials using electron spectrometers. Several experimental campaigns were conducted on peta watt laser facilities at the Rutherford Appleton Laboratory and Osaka University. In these experimental campaigns, the pulse duration was varied from 0.5 ps to 5 ps. The laser incident angle was also changed from normal incidence to 40° in p-polarized. The results show a reduction from the ponderomotive scaling on fast electrons over $10^{20}$ Wcm$^{-2}$.

1. INTRODUCTION

The fast ignition (FI) scheme for inertial confinement fusion was first proposed by M. Tabak [1] in 1994. In FI scheme, when an ultra intense laser (UIL) pulse is irradiated into an imploded plasma, fast electrons are generated from laser-plasma interactions and are used to heat the fuel core. Recently, LFEX laser at Osaka University and OMEGA-EP laser at University of Rochester are constructed for FI integral experiments. These laser intensities exceed $10^{20}$ Wcm$^{-2}$. Moreover, pulse duration becomes about 10ps and longer than previous experiment. Therefore, in these conditions, the characteristics of fast electrons should be studies.

We deduced slope temperatures from the measured fast electron spectra and compared those with pondero motive scaling in the range $10^{18}$ Wcm$^{-2}$ to $10^{21}$ Wcm$^{-2}$.

2. EXPERIMENT

The experiments were performed using both the VULCAN peta watt (VULCAN PW) [2] and Gekko XII peta watt (GXII PW) laser systems [3]. The VULCAN PW has a measured intensity contrast ratio of $4 \times 10^{-8}$ and delivered pulses in the range 0.5 – 5 ps. Laser pulses with up to 300 J were delivered on target. The wavelength was 1.054 μm. The laser was focused onto target using an f/3 parabola and the spot size was 7μm Full Width at Half Maximum (FWHM). 20% of the laser energy was contained within that focal region [4]. The laser intensity is changed from $10^{18}$ Wcm$^{-2}$ to $10^{21}$ Wcm$^{-2}$ by varying the energy delivered and the pulse duration. The laser was incident at both normal (0°) and p-polarized 40°. The GXII PW has a measured intensity contrast ratio of $1.5 \times 10^{-8}$. The pulse duration was between from 0.6 to 0.7 ps. Up to 100 J was delivered on target. The wavelength is 1.053μm. The laser was focused onto target using an f/7.6 parabola and the spot size was 15 μm FWHM. The laser intensity was from $10^{18}$ Wcm$^{-2}$ to $10^{19}$ Wcm$^{-2}$. The laser was incident at an angle of 26° to the target normal [5].

These experiments used a variety of target materials in both single and multilayer structures. The interaction surfaces of target were Cu, Au, Al and Ti and the target thickness ranged from 5 μm to 100 μm. Two different electron spectrometers (ESM) were used for the fast electron spectrum characterization. The ESM was placed behind the target and measured the fast electron energy spectra. Fuji film imaging plates were used as the detectors. In spite of such broad range of conditions, only the laser intensity showed a clear dependence on the temperature.

Electron spectra were measured along the laser axis. The measured energy spectra were fitted with a relativistic Maxwellian distribution with the electron temperature $T$ of the form \[ N(E) = N_0 E^2 \exp(-E/T). \] Here $N_0$, $E$ and $T$ are the electron number, the electron energy and the electron temperature, respectively.

Figure 1 shows the measured fast electron slope temperature versus the incident laser intensity. The experimental results are compared with the Wilks’ ponderomotive scaling of the form \[ T(E) = T_0 \exp(-E^2/T_0^2). \]
$T[\text{MeV}] = 0.511 \left( \sqrt{1 + I_{18} \lambda_{\mu m}^2 / 1.37} - 1 \right)$, where $T$, $I_{18}$ and $\lambda_{\mu m}$ are the electron temperature, the laser intensity in units of $10^{18}$ Wcm$^{-2}$ and the wavelength in microns, respectively. The dotted line is the calculation of the electron temperature from this ponderomotive scaling. The broken line is Haines’ relativistic model. The solid line shows a least square fitting on the data.

In Fig. 1, the data shows a clear departure from the Wilks’ scaling. The fast electron temperature becomes lower than ponderomotive scaling. In a most recent study of fast electrons measured both within targets and at ESMs show that the spectra are very much alike [9]. It is of great importance to point out here that this scaling is in favor for fast ignition up-coming integral experiments; rather high irradiation laser intensity can be used to generate fast electrons within a modest slope temperature. Those experiments will use 1-10 ps ultra-intense laser pulse to fast heat a highly compressed fuel to achieve several keV core temperature [10,11].

A least squares fit to the experimental points provides almost the $I^{1/3}$ fit, as shown in Figure 1, but some consideration is needed in the interpretation of this scaling. In the absorption region, fast electron energy distribution is of particular concern since a number of recent computational studies have shown the fast electron spectrum softens with time. Those simulations indicate that this softening results from the preformed plasma in the corona being swept away by the ponderomotive force early in the interaction, even with pico second duration pulses. Thereafter, the excursion distance of electrons pulled from the skin layer is much smaller than the full laser wavelength, resulting in the reduced mean energy [12,13]. We believe that the main part of the acceleration is performed by the $v \times B$ force even though we believe that our experiments suffer little effect of pre-plasmas. Especially the relatively long laser pulse may sweep up any plasma in front of the solid surface and then the laser starts facing its effective critical density plasma whose charge states are determined by the laser heated temperature at the area. If this situation is realized, the fast electron temperature may drop further [12,13]. As discussed in several works, the pre-pulse may alter the characteristics of ultra-intense laser matter interactions drastically [14,15]. Pre-pulse level of this experiment can be seen in Fig. 10 in Ref. 16 which shows that the interactions should occur at the effective critical density.

![Figure 1.](image-url)

Figure 1. Plot of the measured electron temperature as a function of intensity on target. Also shown is the ponderomotive scaling as dotted line [8] and Haines’ relativistic model as broken line [19]. A least square fit to the data as solid line shows that the fast electron temperature scales as $T[\text{MeV}] = 0.4 \left( I_{18} \lambda_{\mu m}^2 \right)^{1/3}$. 
A novel explanation is briefly reviewed for the $I^{1/3}$ intensity scaling in Fig. 1, one that reproduces previous results up to $10^{19}$ Wcm$^{-2}$ [17] as well as more recent Bremsstrahlung radiation measurements of electron entering the target up to $10^{21}$ Wcm$^{-2}$ [18]. The laser-plasma interaction region is treated as a one-dimensional ‘black box’, the thickness of which is a few collision less skin-depths. Relativistic conservation equations are then applied to this region, rather in the same way as in a shock transition. This very simple model leads to Haines’ relativistic model. This model is discussed in detail in Ref. 19. The scaling based on the relativistic model shows very good consistency with the experiment within the laser intensity range between $I = 10^{18}$ and $I = 10^{21}$ Wcm$^{-2}$ in Fig. 1.

3. CONCLUSION
In conclusion, the electron temperature of fast electron escaping to an electron spectrometer located on the target chamber wall has been measured for a variety of different laser conditions using two different peta watt laser facilities. These new results are consistent with both Bremsstrahlung radiation measurements generated from electrons entering the overdense plasma [18] as well as analytic models that include both energy and momentum conservation [19]. It has been found that the departure from the ponderomotive scaling of the fast electron temperature as a function of intensity on target is robust and occurs under a range of different irradiation conditions. The obtained scaling gives a wider range of laser intensity window for modest temperature of fast electrons that could be utilized for designing up-coming integral fast ignition experiments compared the one based on the ponderomotive scaling.

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