Fast electron beam measurements from relativistically intense, frequency-doubled laser–solid interactions

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Abstract. Experimental measurements of the fast electron beam created by the interaction of relativistically intense, frequency-doubled laser light with planar solid targets and its subsequent transport within the target are presented and compared with those of a similar experiment using the laser fundamental frequency. Using frequency-doubled laser light, the fast electron source size is significantly reduced, while evidence suggests the divergence angle may be reduced. Pyrometric measurements of the target rear surface temperature and the Cu K\textsubscript{α} imager data indicate the laser to fast electron absorption fraction is reduced using frequency doubled laser light. Bremsstrahlung measurements indicate the fast electron temperature is 125 keV, while the laser energy absorbed into forward-going fast electrons was found to be 16 ± 4% for frequency doubled light at a mean laser intensity of 5 ± 3 × 10\textsuperscript{18} W cm\textsuperscript{-2}.

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1. Introduction

When a relativistically intense laser pulse irradiates a solid target, large numbers of fast electrons are generated. The kinetic energy these fast electrons acquire during the interaction has been found to be close to that of electrons oscillating in the transverse field of the incident light wave [1–3]. If the picosecond-duration laser pulse is preceded by a longer duration, lower intensity pedestal (caused by amplified spontaneous emission (ASE)), then a coronal plasma is formed around the interaction point some time before the relativistic pulse arrives. In these circumstances, it is possible for the fast electrons to acquire substantially higher energies [4–6] via collective acceleration processes in the finite density gradient plasma.

The understanding of the fast electron beam generated by intense laser–plasma interactions and its subsequent transport is an interesting area of fundamental physics. Furthermore the detailed characterization of the fast electron beam and its transport under controlled conditions is important for numerous applications including proton and ion beam production [7–10], isochoric heating of high density matter for opacity studies [11–15], and fast ignition inertial confinement fusion [16–21]. Fast electron energy transport is dictated by the resistivity and
density of the medium in which the transport is occurring, the fraction of laser energy absorbed into fast electrons, the fast electron source size, their divergence and the fast electron energy spectrum.

The majority of relativistic laser–solid interaction experiments performed to date have used lasers with a wavelength of 1064 or 800 nm. Frequency doubling is possible with nonlinear crystals such as potassium di-hydrogen phosphate. Baton et al [22] inferred from Kα measurements that the acceleration of electrons into a cone–wire type target was significantly enhanced by frequency conversion to 2ω₀. This enhancement was attributed to the reduction in the nanosecond duration ASE which precedes the main high intensity pulse; the nonlinear frequency doubling process is only effective for the highest intensity part of the pulse, hence the ASE, which is typically five orders of magnitude smaller in intensity, will not be frequency doubled and can be easily removed after the crystal using 1ω₀ mirrors.

Baton et al [22] attributed the detrimental effects of the ASE to the ablation of the cone inner surface. This fills the cone with plasma prior to the arrival of the main pulse, thereby displacing the critical surface from the solid surface. As the fast electron source is divergent, the fast electron density, and hence energy density, measured at a given point within the target will be lower. By reducing the ASE, the high intensity pulse interacts with a far smaller density scale length (DSL) than would otherwise have been possible until very recently using a 1ω₀ laser.

This paper describes fast electron beam and transport measurements from an experiment using frequency-doubled (2ω₀), relativistically intense laser light to irradiate a solid target. Subsequently a detailed comparison is made between this 2ω₀ data and experimentally measured fast electron characteristics from a similar 1ω₀ experiment [5] previously performed on the same laser facility. For the 2ω₀ experiment, the measured bremsstrahlung radiation spectrum and energy deposition is back-out using three-dimensional Monte Carlo modelling, allowing the experimental fast electron temperature and fraction of laser light absorbed into fast electrons to be inferred.

2. Frequency doubled, relativistically intense, laser–solid experiment

An experiment was performed at the LULI 2000 laser facility at the École Polytechnique in Paris in order to characterize the properties of the fast electron beam generated when relativistically intense frequency-doubled laser light interacts with a solid target and its subsequent transport within the target. The diagnostics used were: absolutely calibrated bremsstrahlung detectors [23, 24], Cu Kα imaging and spectroscopy [5] and spatially and temporally resolved rear surface pyrometry [5]. Twenty five Joules of 527 nm light was incident on the target at 45° p-polarization, with a pulse length of 800 fs and spatial full-width-at-half-maximum (FWHM) of 15 μm yielding a peak intensity of 9 × 10¹⁸ W cm⁻² and mean intensity (found by spatially and temporally averaging the Gaussian distributions over the spatial and temporal FWHM, respectively) of 5 × 10¹⁸ W cm⁻². It was not possible to directly measure the contrast of the laser, but miro laser amplification and propagation modelling [25] indicates the 2ω₀ pre-pulse energy was 4 × 10⁻⁵ J over 2.5 ns.

A variety of 5 mm × 5 mm, planar targets were used for the experiment. For the purposes of the absolute laser absorption measurements, the target were composed of Al (10 μm), Ag (10 μm), Au (10 μm), Cu (10 μm), Al (10 μm) and CH (300 μm), with the laser incident on the first Al layer. Absolute bremsstrahlung radiation measurements require the prevention of refluxing as multiple transits of the electrons within the target will cause multiple
bremsstrahlung emissions from within the target. Monte Carlo modelling of an appropriate fast electron energy distribution indicates the majority of the fast electrons are stopped within 600 µm of plastic. Accounting for refluxing from the target rear, a single pass of fast electrons passing through the high Z material is achieved by attaching a 300 µm mylar layer to the target rear. For the rear surface pyrometry measurements, either planar pure Al targets or Al backed with 5 or 10 µm of Cu and a 1 µm Al tamping layer were used, with various thicknesses of Al.

The bremsstrahlung spectra and angular distribution were measured using three of the detectors detailed in [23] as shown in figure 1. Based on the work of Santala et al [26] it was anticipated that the peak bremsstrahlung emission would occur along the target normal direction given the high experimental contrast, so one detector was positioned along the laser axis and then at two 22.5° increments with the third detector at target normal. Magnets were positioned such that all electrons with energies less than 40 MeV were prevented from entering the detectors.

The Cu Kα x-rays emitted from the Cu layer of the targets were imaged with a spherically bent quartz 2131 crystal (2d = 3.082 Å) with the radius of curvature RC = 380 mm. This crystal only reflects the Kα₁ line at 8048 eV, and has a central Bragg angle of θ₀ = 87.3° ± 0.1°. The setup gave a magnification of 11, and is integrated in time. The aperture diameter size on the crystal was 15 mm at the beginning of the experiment, but was changed to 25 mm to get more signal. Cross calibration was used to compare the data before and after this alteration.

F/4 optics at 20° from target normal collected the visible optical emission from the target rear surface caused by Plankian thermal emission. This was recorded with a time resolved two dimensional (2D) imager (HISAC) [27]. In this setup HISAC had a spatial resolution of 70 µm, a temporal resolution of ~15 ps and a multi-frame capability spanning 2 ns. As the
temporal resolution is a function of the spectral bandwidth of the signal (due to dispersion within the fibre-optics), a bandpass filter centred at 460 nm with a 40 nm FWHM, was used in order to cut out non-Plankian signals (e.g. at the harmonics of the incident laser) and minimize the bandwidth of the region of the Plankian that was measured, while ensuring there was sufficient signal. Calibration was performed with an absolutely calibrated emission lamp, and temperatures backed-out, using the process detailed in [5].

For Cu Kα spectroscopy, a potassium acid phthalate (KAP) conical crystal with a focal length of 310 mm and 2\(d\) spacing of 26.64 Å focused the 6.85–8.5 keV (fifth order) Cu Kα\(_1\) and Kα\(_2\) x-rays onto an image plate [28]. The fast electrons ionize the Cu K-shell, while the relative amplitudes of the emitted Kα\(_1\) and Kα\(_2\) lines are dictated by the density and temperature of the bulk target plasma. This spectral line measurement is integrated over time and the flour layer volume. The buried Cu layer of the target is 10 \(\mu\)m thick, and located 1 \(\mu\)m below the target rear surface, consequently, although these results might be expected to be similar to those obtained using the rear surface pyrometry, the two measurement locations are slightly spatially offset.

3. Experimental results

The primary objective of this experiment was to characterize the fast electron beam generated by a 2\(\omega_0\) laser–solid interaction in order to compare it with that generated by a 1\(\omega_0\) laser. It was not possible to take 1 and 2\(\omega_0\) shots on the same experiment, meaning any comparisons rely on the accurate calibration of the experimental diagnostics. This section summarizes the key results from the frequency-doubled experiment, and where possible compares them with 1\(\omega_0\) experimental data detailed in [5], subsequently referred to as the variable DSL 1\(\omega_0\) experiment.

In brief, the characteristics of the 1\(\omega_0\) experiment were: 40 J of laser energy on target, a peak intensity of \(2 \times 10^{19}\) W cm\(^{-2}\), with three ASE energy contrasts (3 \(\times\) 10\(^{-3}\), 6 \(\times\) 10\(^{-3}\) and 1 \(\times\) 10\(^{-2}\)) used to pre-expand the target front surface, creating three different DSLs, with which the main pulse interacted in the lead-up to the solid target. This is described in detail in [5].

3.1. Target rear surface temperatures

Figure 2 compares the 2\(\omega_0\) pyrometry data with the results from the 1\(\omega_0\) experiment described in [5] where the DSL was varied. The 2\(\omega_0\) results are similar to those obtained with the highest contrast on the variable DSL 1\(\omega_0\) experiment, although there is significant scatter in both datasets. It should be noted that the contrast in the 2\(\omega_0\) experiment is expected to have been a lot higher than the best in the 1\(\omega_0\) experiment, although unfortunately this could not be measured directly.

Figure 3(a) shows the temperature within the Cu fluor layer at the target rear after being normalized to the laser energy on target to facilitate comparison of the two experimental datasets. The bulk electron temperatures within the Cu fluor layer were inferred by firstly generating a series of synthetic spectra using the non-local thermodynamic equilibrium (LTE) code flychk [29]. Each synthetic spectrum corresponds to an assumed bulk electron temperature at the target solid density. A least squares fit of the synthetic spectra against the experimental data provided the best match and hence an inference of the experimental temperature. Unlike the pyrometry (figure 2), the temperatures inferred from the Cu Kα spectroscopy indicate the laser energy normalized rear surface temperature produced with 2\(\omega_0\) light is approximately double that produced with 1\(\omega_0\) laser light. Figure 3(b) depicts the
actual temperatures inferred from the spectra using flychk. Interestingly, within the error bars the temperatures from both experiments are almost identical, furthermore accounting for the error bars there is little, if any, variation in temperature with thickness. This means any apparent enhancement with $2\omega_0$ light, as expressed in eV J$^{-1}$, is entirely due to the difference in laser energy on target used to normalize the temperature values. Whilst this may simply be coincidence, the fact that there is no temperature variation with thickness is very surprising given that the pyrometry observed a ten-fold decrease in temperature going from 10 to 50 $\mu$m. A significant body of previous research shows a sharp increase in the target temperatures for thicknesses below $\sim$20 $\mu$m—very similar to that observed pyrometrically.

The discrepancy between the temperatures derived via the pyrometer and those from the Cu K$_\alpha$ spectroscopy may be due to temporal and spatial integration effects. The Cu K$_\alpha$ spectrometer integrates over a large volume of plasma which is made up of many bulk electron temperatures, hence the emitted spectrum is averaged over a large volume, this may cause the Cu K$_\alpha$ spectrometer to be insensitive over the range of this experiment. Another important consideration is that based on flychk, the Cu K$_\alpha$ lines simply do not change very much over the experimental temperature range (as inferred from the pyrometry)—this would act to compound any insensitivity. Based on the above, the authors would advise caution in the interpretation of figure 3(a).
Figure 3. Comparison of the $2\omega_0$ experiment temperature data derived from the conical spectrometer data with previous data from the variable DSL $1\omega_0$ experiment: (a) temperatures normalized to laser energy on target and (b) inferred (unnormalized) temperatures.

Figure 4. Comparisons of the $2\omega_0$ dataset to the data from the DSL experiment performed at $1\omega_0$: (a) HWHM of the rear surface thermal emission and (b) 2D $K_{\alpha}$ imager HWHM. Note the vertical axes of (a) and (b) are not the same.

3.2. Fast electron divergence

Figures 4(a) and (b) depict the half-width-at-half-maximum (HWHM) of the rear surface thermal emission and 2D $K_{\alpha}$ imager data from the $2\omega_0$ experiment in comparison to the
Table 1. Linear fits to the HWHM extracted from the Kα imager and rear surface pyrometry data. In order to minimize anomalous measurements caused by the effects of refluxing, only targets with thickness greater than 10 µm have been included for the fits. Approximate errors due to scatter in the datasets are shown in brackets. These do not refer to the difference between the measured values and the true propagation angle of the fast electron beam. The 2ω₀ data from both diagnostics suggest the divergence half angle is reduced, furthermore the fast electron source size (the HWHM extrapolated to the target front) is also smaller.

| Diagnostic | Divergence half angle (°) | HWHM at target front (µm) |
|------------|--------------------------|--------------------------|
|            | HISAC (±9°)   | Kₜ (±7°)    | HISAC (±10%) | Kₜ (±5%) |
| Small DSL  | 34           | 26          | 188         | 59       |
| Medium DSL | −20          | 39          | 156         | 44       |
| Large DSL  | 39           | 32          | 95          | 48       |
| 2ω₀        | 18           | 12          | 24          | 33       |

Experimental data from the DSL experiment performed at 1ω₀ [5]. The 1ω₀ results are similar to others’ (e.g. [30]) but the FWHM are somewhat larger than those of Vazour et al [31]. As shown in Table 1, in comparison to the 1ω₀ dataset, the 2ω₀ data shows a significant reduction in the HWHM of their respective emission regions for both diagnostics. There is also an apparent reduction in the divergence half angle although this is less clear given the error bars resulting from scatter in the data. The linear fits to the HWHM data (which give the divergence angle) do not include targets of thickness <10 µm in order to reduce the effects of refluxing, as this artificially inflates the apparent fast electron source size for the thinnest targets. Were the data from the thinnest targets to be included, the fast electron beam would appear to converge. While this is not necessarily unphysical given the likely presence of large self-generated magnetic fields, no such inference can, or should, be made based on this dataset. The reduced measured divergence with 2ω₀ light cannot be solely attributed to the frequency doubling as the peak intensity of the interaction has also been reduced by ~2.2 ×. According to the intensity-divergence scalings published by Green et al [32], a small reduction in divergence might be expected due to the change in intensity, but this would be significantly less than the measured divergence reductions which are approximately 15°. This suggests that frequency doubling reduces the fast electron divergence angle. However as the data published by Green et al was all measured on 1ω₀ lasers, the intensity axis could equally have been that of Iλ². The Iλ² of the 2ω₀ experiment was ~10 × lower than that of the 1ω₀ experiment, based on this (and assuming an Iλ²-divergence version of Green et al’s plot), the expected half-angle reduction due to the lower Iλ² would be 5–10°. The measured divergence reduction is approximately 15°, indicating there may be a small further reduction over that expected due to the Iλ² reduction. Given the error bars this result is uncertain.

Particle-in-cell (PIC) modelling performed for the variable DSL 1ω₀ experiment [5] showed that refraction of the laser within the underdense plasma in the lead up to the 45° polarized target causes the fast electron source width to be significantly increased. This refraction would be minimized by the small DSLs associated with the frequency-doubled
laser, hence the observed reduction in the spot width is partly attributed to a reduction in the fast electron source width due to the elimination of refraction. The reduced ASE caused by frequency doubling will also mean the critical surface will be closer to the target front surface. By reducing the offset of the source from the target, the apparent source width (as measured at the target front) of a diverging beam will be reduced. Other effects which will further reduce the laser focal spot width are also caused by the frequency doubling of the laser light which reduces the diffraction limit of the focal spot size. The fast electron temperature is expected to be significantly reduced in the $2\omega_0$ experiment due to the reduction in $I\lambda^2$, this may also reduce the effects of refluxing, further reducing the apparent fast electron beam width. The trends in the source size as a function of DSL are discussed in detail in [5]. With the available data it is not possible to isolate one cause for the observed reduction in the fast electron source width.

3.3. Other fast electron characteristics

Figures 5(a) and (b) show the variation in the peak and spatially integrated Cu K$_\alpha$ imager signal respectively as a function of fluor layer depth. The peak Cu K$_\alpha$ imager signal is approximately proportional to the peak fast electron number density, although as the Cu K$_\alpha$ collisional cross-section peaks at $\sim$20 keV [33], this measurement is slightly biased towards the lower energy fast electrons. Measurement of the relative Cu K$_\alpha$ emission using the monochromatic imager can potentially be complicated by a change in the bulk target electron temperature, as this can cause the Cu K$_\alpha$ line to shift and change in magnitude [34]. However the experimental temperatures derived from both temperature diagnostics indicate this will not affect the measurement significantly over the experimental temperature range. The data has been normalized to the laser energy on target to facilitate comparison with the experimental results obtained from the variable DSL $1\omega_0$ experiment. Over the range of target thicknesses where the data can be compared, figure 5(a) shows that the peak signal is very similar between the
two datasets, indicating there is no clear enhancement in peak flux per Joule of laser energy on target, despite the significant reduction in the fast electron beam HWHM.

Figure 5(b) shows the total Cu Kα emission (the spatially integrated Cu Kα imager signal) per Joule of laser energy on target. Within this experiment’s temperature range, the total signal is approximately proportional to the fast electron number. This data indicates the fast electron number is reduced in the 2ω0 case, suggesting the fraction of the laser energy absorbed into fast electrons is also reduced.

3.4. Fast electron energy spectrum

The complex procedure to find the fast electron energy spectrum is described in detail by Scott et al [23]. In brief, the target materials, densities, geometry and detector geometry from this experiment were modelled in three dimensions within the Monte Carlo particle transport code MCNPX [35]. A series of fast electron distribution functions described by single-temperature relativistic Maxwellians were ‘injected’ into the target. Each distribution function has a different assumed fast electron Maxwellian slope temperature. The simulated fast electrons propagate within the target generating bremsstrahlung radiation. The bremsstrahlung radiation then propagates through the various filters of the detector, before depositing energy within the phosphor layer of the detector. By utilising 25 filters of varying thickness, the ‘shadows’ cast by the filters on the image plate create 25 energy bins. The experimentally measured energy deposited within each bin of the phosphor layer of the detector is then compared with the simulated relative energy deposition within the phosphor layer using a least squares fit. The fast electron temperature is established by performing this least squares fit for each simulated fast electron temperature injected into the target, thereby establishing the best fit. Figures 6(a) and (b) show the relative energy deposition within the different spatial regions of the image plate (each region corresponds to an energy bin) as a function of fast electron temperature. The experimentally measured values are also over-plotted. The best fit to the experimental data was a fast electron temperature of 125 ± 25 keV for all detector angles. For the purpose of evaluating the fast electron temperature only the relative values of the energy deposition in each bin is important, hence arbitrary units are used.

3.5. Laser energy absorbed into fast electrons

A detailed process to extract the laser energy to fast electron absorption fraction from the bremsstrahlung data is detailed by Scott et al [23]. In brief the laser energy to fast electron absorption fraction is calculated as follows: given the previously determined fast electron temperature, the total modelled bremsstrahlung energy deposited in the image plate phosphor layer per source electron is found by integrating over the phosphor volume. Using the image plate absolute calibration, the total number of fast electrons required to create the measured signal is calculated. The mean fast electron energy is calculated from the fast electron temperature and distribution function. Finally the total energy of the fast electron distribution is found by multiplying the number of electrons by the mean fast electron energy. The fraction of the laser energy absorbed into forward-going fast electrons was found to be 16 ± 4%. It should be noted that because the target producing the bremsstrahlung radiation only covers the region of solid angle in the forward direction with respect to the incident laser, this technique only measures laser energy absorbed into fast electrons which are forward-going. The principal
Figure 6. The data from shot 40 (detector at target normal) is compared to the modelled detector response for two initial relativistic Maxwellian electron temperatures. The experimental data is the mean photo stimulated luminescence (PSL) value within each ‘region’ of the image plate, a region exactly corresponds to the shadow cast by one of the filters onto the image plate, likewise the mcnpx values shown are the mean energy deposition within the same location and area of the modelled image plate’s phosphor layer.

Sources of error were due to the uncertainty in the relativistic Maxwellian temperature (and the associated mean electron energy), and the image plate calibration. The variance of the MCNPX modelling was relatively small at <0.7%.

When using this technique it is crucial that the modelled response of all the detectors matches that of the experimental data as otherwise this technique would give incorrect results. In this case, the bremsstrahlung emission was found to be relatively isotropic over the forward hemisphere. The near isotropic emission gives added confidence that any important spatially varying features of the experimental data have been captured despite the limited solid angle covered by the detectors, and hence that the inferred absorption fraction should be accurate. The laser energy absorption fraction was calculated separately for each detector and found to be consistent within ±1%, indicating the modelled bremsstrahlung emission accurately matches that of the experiment.

3.6. Discussion

In comparison to a $1\omega_0$ laser–solid interaction, the frequency doubled laser yields a clear reduction in the inferred fast electron source size based on both the Cu Kα imager and thermal emission diagnostics. There is also a suggestion of a reduction in the fast electron divergence angle, although given the anticipated reduction in divergence with laser intensity (or $I\lambda^2$)
on target, combined with the experimental errors, this is yet to be proven conclusively. The peak Cu Kα emission is comparable to that at 1ω₀ while the integrated signal is reduced. The pyrometry indicates that the laser energy normalized target rear surface temperatures are unchanged with respect to the highest contrast data from the 1ω₀ experiment. While the laser energy normalized Cu Kα spectroscopy indicates a doubling in the target rear surface temperature when using frequency-doubled light, this result may be incorrect due to the spatial integration of the spectrometer causing a lack of sensitivity. These results are broadly consistent with reduced laser absorption into fast electrons when using frequency doubled light, as despite the significant reduction in the fast electron source size and suggestion of reduced fast electron divergence, the target rear surface temperatures and peak Cu Kα imager signal are not increased. This is corroborated by the reduction in the laser-energy-normalized spatially integrated, or total, Cu Kα imager signal with frequency doubled light. This may be due to the reduction in laser intensity on target in the frequency-doubled experiment (see below). Frequency doubling will significantly reduce Iλ₂ due to the inefficiency of the conversion process (30% in this experiment) and the reduced wavelength, hence the fast electron temperature should be lower in the 2ω₀ case. This reduction in the fast electron temperature in going to 2ω₀ would be expected to increase the total fast electron number (or laser energy normalized total Cu Kα signal) for an equivalent laser absorption fraction, as the reduced mean fast electron energy caused by the reduction in the fast electron temperature should result in an increased number of fast electrons.

The inference that the laser absorption into fast electrons is reduced when using frequency doubled light is superficially at odds with the results of Baton et al [22]. This may be due to the differing geometries of the two experiments; Baton et al ascribed the reduced coupling to pre-plasma, caused by ASE induced ablation filling the cone prior to the arrival of the short-pulse interaction beam. In comparison to the re-entrant cone geometry, the planar target geometry explored here will have an increased solid angle into which any pre-plasma can expand, hence any offsetting of the relativistic critical surface will be significantly reduced in the planar geometry case. Consequently any detrimental effects caused by offsetting of the relativistic critical surface will be reduced in this planar geometry.

The bremsstrahlung fast electron temperature analysis yielded a best fit with a relativistic Maxwellian temperature of 125 ± 25 keV. Based on an analysis of the focal spot [36] the temporally and spatially averaged mean laser intensity within the FWHM was found to be 5 ± 3 x 10¹⁸ W cm⁻². A comparison of Beg’s [37], Haines’ [3], Sherlock’s [2] and Wilks’ [38] fast electron temperature scaling laws with the data from this experiment indicates that Sherlock’s scaling best fits the data, while Wilks’ is also within the error bounds of the experimental value. Sherlock’s scaling is the same as that of Wilks but multiplied by 0.6. The reason cited in Sherlock’s work for the fast electron temperature being sub-ponderomotive is that the field which draws the return current also acts upon the laser accelerated fast electrons, reducing their kinetic energy. The fast electron temperature derived from Wilks’ PIC modelling could not (at that time) account for these effects as they require accurate modelling of collisions and resistivity. Beg’s scaling provides a higher fast electron temperature in the experimental range examined here, this may be because the experiments used to derive this scaling law were performed on laser systems with considerably worse contrast. Consequently the higher temperature component associated with those electrons accelerated in the underdense plasma [5, 6] may be proportionately larger, increasing the inferred temperature.

Based on bremsstrahlung measurements, the measured laser energy absorption fraction into forward-going fast electrons was found to be 16 ± 4%. This is lower than measurements
by Ping et al [39] which measured the total laser light absorbed rather than the energy in the forward-going fast electron distribution. This disparity will partly be caused by energy being transferred away from the electrons via processes Monte Carlo techniques cannot model (e.g. ion acceleration, collective field generation). Furthermore the pulse length in Ping et al’s experiment was considerably shorter—such a short pulse may be completely absorbed by any pre-plasma, unlike in the experiments described here. The measured value shows good agreement with the lower intensity measurements of Yasuike et al [40] which rises from 12% at $2 \times 10^{18} \text{ W cm}^{-2}$, to 18% at $10^{19} \text{ W cm}^{-2}$, reaching 50% at $10^{20} \text{ W cm}^{-2}$. The peak and total Cu K$_\alpha$ imager data presented here suggests the fraction of laser energy absorbed into fast electrons may be less at $2\omega_0$ than $1\omega_0$. The cause of this reduced absorption cannot be determined from the available data, although it is likely due to either the frequency doubled light, higher contrast or reduction in laser intensity. Given the aforementioned work of Ping et al and Yasuike et al both found a strong reduction in absorption with laser intensity this is a likely explanation. This will be the subject of a future publication.

For the purposes of comparison, the experimental data from the two experiments were normalized to the laser energy on target, however in this experiment the conversion from red to green light was only $\sim 30\%$ efficient. In the context of fast ignition, where the ‘wall-plug’ efficiency of the laser is critical, such inefficiencies would be unacceptable, however in principle, $2\omega_0$ conversion efficiencies of the order of $\sim 80\%$ are achievable. The observed reduction in the fast electron source size would be advantageous for fast ignition, as it increases the geometrical coupling from the laser absorption surface to the region of the deuterium–tritium core which is being heated. The fast electron current density appears similar for both $1$ and $2\omega_0$ light. Accounting for all of the observed characteristics of the fast electron beam, frequency doubled light may be the better candidate for a fast ignition ignitor beam as this will be accompanied by a $4\times$ reduction in $I\lambda^2$ with the associated reduction in fast electron temperature for a given laser intensity.

3.7. Summary

In summary, experimental measurements of the fast electron beam created by the interaction of relativistically intense, frequency-doubled laser light with planar solid targets and its subsequent transport within the target have been made. In comparison to similar measurements made using the laser fundamental frequency, the fast electron source size is significantly reduced, while evidence suggests the divergence angle may be reduced. However pyrometric measurements of the target rear surface temperature and the Cu K$_\alpha$ imager signals indicate the laser to fast electron absorption fraction was reduced using the lower intensity frequency doubled laser light. The cause of this reduced absorption cannot be determined from the available data, but is likely due to the frequency doubled light, higher contrast or reduced laser intensity. Using bremsstrahlung measurements the fast electron temperature was found to be $125\text{ keV}$, while the laser energy absorbed into forward-going fast electrons was found to be $16 \pm 4\%$ at a mean intensity of $5 \pm 3 \times 10^{18} \text{ W cm}^{-2}$.

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