Enhanced He-α emission from smoked Ti targets irradiated with 400nm, 45fs laser pulses

F Y Khattak, O A M B Percie du Sert, D Riley

School of Mathematics and Physics, Queen's University of Belfast, Belfast, BT7 1NN, N. Ireland, UK

M Edwards, P Mistry, G Tallents

Department of Physics, University of York, Heslington, York YO10 5DD, UK

P S Foster, R J Clarke, E J Divall, C J Hooker, A J Langley, D Neely, J M Smith, C Spindloe, M K Tolley

Central Laser Facility, CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX, UK

Main contact email address: *f.khattak@qub.ac.uk*

Introduction

Ultra-short laser pulses, created by chirped pulse amplification (CPA)[1], allow for the creation of high density and high temperature plasmas confined to a small volume. The interest in such plasmas is partly driven by their potential for bright short bursts of X-ray radiation[2,3] with applications in biology and medicine[4,5] microlithography[6], plasma dynamics[7] , X-ray lasers[8], and x-ray diffraction and scattering[9-12]. Efforts to increase the efficiency of such sources, such as modulating the target surface by various means, have been employed[13-21]. Rajeev *et al.*[19] have demonstrated 13-fold enhancement in the bremsstrahlung X-ray yield in the 10-200keV range using targets coated with copper nanoparticles. Nishikawa *et al.*[20] have shown about 10-fold enhancement in the yield of Si K-α emission from a Si target coated with carbon nanotubes. Their data, however, does not give absolute yields.

Kulcsár *et al.*[21] have compared emission from Ni targets with different surface structure and demonstrated a 50 fold increase in the broadband X-ray yield in the sub-keV region with 1ps pulses. This was achieved with low density, "smoked" targets which are made by thermal deposition of a metal in an inert atmosphere[22]. They observed that the FWHM of the broadband XUV (>150eV) radiation lasted 70ps as compared to 25ps for nanowire and grating targets and 10ps from the flat Ni target.

For some applications it is desirable to have a quasi-monochromatic source such as K-alpha or thermal X-ray line emission. Here we report on experiments demonstrating enhancement of the line radiation at ~4.75keV with a spectral resolution better than 10eV and temporal resolution of ~2ps. With single shot time integrated absolute yield data, we demonstrate up to a 20-fold increase in He-α line ($1s^2$-$1s2p\ ^1P$ and satellites) emission (4.7-4.75keV) from low density "smoked" Ti targets compared to commercially available Ti foils.

Experimental

The experiments were carried out at the Rutherford Appleton Laboratory using the Astra laser facility, delivering up to 0.5J in 800 nm, p-polarized pulses of 45(±5) fs duration. A 0.6 mm thick type-I KDP crystal was employed to convert the IR beam into second harmonic, 400 nm (blue), s-polarized pulses. A beam splitter reflecting the blue and transmitting the IR, was used at 45º to relay the blue beam onto the target. Two dielectric mirrors in the beam-path further reduced the IR component on target. Such conversion immensely reduces the level of pre-pulse, ASE and CPA pedestal[23] and gives a clean laser-solid interaction. For the thin crystal used we expect only a few fs increase in pulse width but it was not possible to measure this at 400nm with an auto-correlator. The conversion efficiency to blue was about 20% and in excess of 60 mJ was achieved on target. The orientation of the target plane was controlled to select either s or p-polarized pulses for interaction with the target surface.

An f/2.5 off-axis silver-coated parabola was used to focus the 400 nm beam at an angle of 45º from the normal to the target plane. Focal spots at different offsets were recorded in the low energy mode of the laser with an 8-bit CCD coupled with a x40 microscope objective. The full width at half maximum (FWHM) of the focal spot at the best focus was measured to be ~2 μm containing about 35% of the total energy. A collinear diode laser beam was injected via one of the dielectric mirrors to form the basis of a retro-alignment system that allowed us to find the best focal spot whenever the target foil was moved to a fresh position. The focal spot on target was varied by moving the parabola off the best focus position along the line-of-focus both towards and away from the target (positive off-set and negative off-set respectively). With negative off-set a convergent beam interacts with the target while in case of the positive off-set the focus lies before the target and a divergent beam interacts with the target. Away from best focus, the focal spot broke up into hotspots and, therefore, the energy distribution in the focal spot changed. The energy on target was monitored via leakage from one of the dielectric mirrors with a fast diode and integrating sphere. At best focus, the intensity reached a maximum of ~10^{19} W/cm^2.

We used 12.5 μm thick Ti and smoked Ti deposited on Al substrates as our targets. The smoked targets were fabricated by evaporating Ti in an ambient environment of argon gas at 2-10 Torr. The depth of the Ti deposited on the substrate was ~20μm. The scanning electron micrographs of the foil target and smoked Ti are shown in Figure 1. The surface of the smoked target appeared black in visible light and the micrograph depicts structures having size smaller than the wavelength (400nm) of the irradiating beam. An AFM scan of the foil target showed a surface smoothness better than 15nm rms over the focal area.

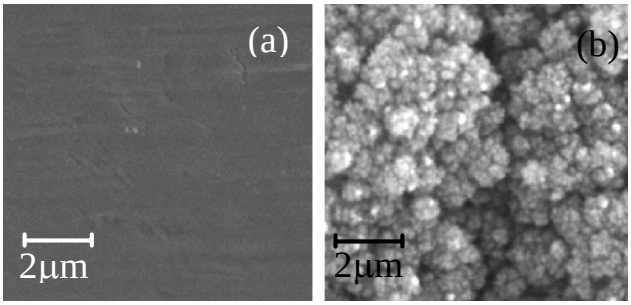

Figure 1. SEM micrographs showing the surface of (a) Commercially purchased Ti foil target and (b) smoked Ti.

After every shot, the target was moved, by 1mm for foil and 2mm for smoked targets, to ensure the beam interacts with a fresh target surface. In all cases, the beam was tight focused on the target, using the retro viewing system, before moving the parabola to the desired offset position. A thin glass pellicle protected the parabola from plasma debris. The time integrated He-like line emission of Ti was recorded on individual shots with a Von- Hamos crystal (LiF 200) coupled to a 16-bit x-ray

CCD system. This system has been calibrated previously at 5.9keV[24] using an Fe^{55} source. A Von-Hamos PET crystal spectrometer coupled to a Kentech x-ray streak camera with a temporal resolution of 2ps was used to record the time resolved He-α emission. The streak camera was fitted with a KBr photocathode and the output was recorded with an intensified CCD system.

Results and discussion

Figure 2 (a) compares absolute He-α yield from Ti foil and smoked Ti both irradiated with 400nm, s-polarized pulses at 45° incidence as a function of focus position. The data points are an average of 3 or more shots and the standard error bars are shown. The error bar in the focal position is ±20 μm. The yield at best focus for the smoked targets case corresponds to a conversion efficiency of ~ $2x10^{-4}$. At around the best focus, the He- α yield from the smoked Ti target is about 20X greater than that from Ti foil target. In Figure 2(b) we show a similar comparison for p-polarized pulses where the results from the two target types are comparable at best focus. However, as can be seen from the error bars there was a significant shot to shot variation in the yield which makes the He-α emission from foil targets unpredictable. Furthermore, He- α emission from the foil target drops very quickly in a FWHM of ~50μm as we go away from the focus, whereas the emission from smoked targets remains high and relatively predictable despite the break up of the beam, out to more than 200μm from best focus. From the standard error bars, it seems that the break up of the beam into hot-spots at high defocus does not adversely affect reproducibility significantly.

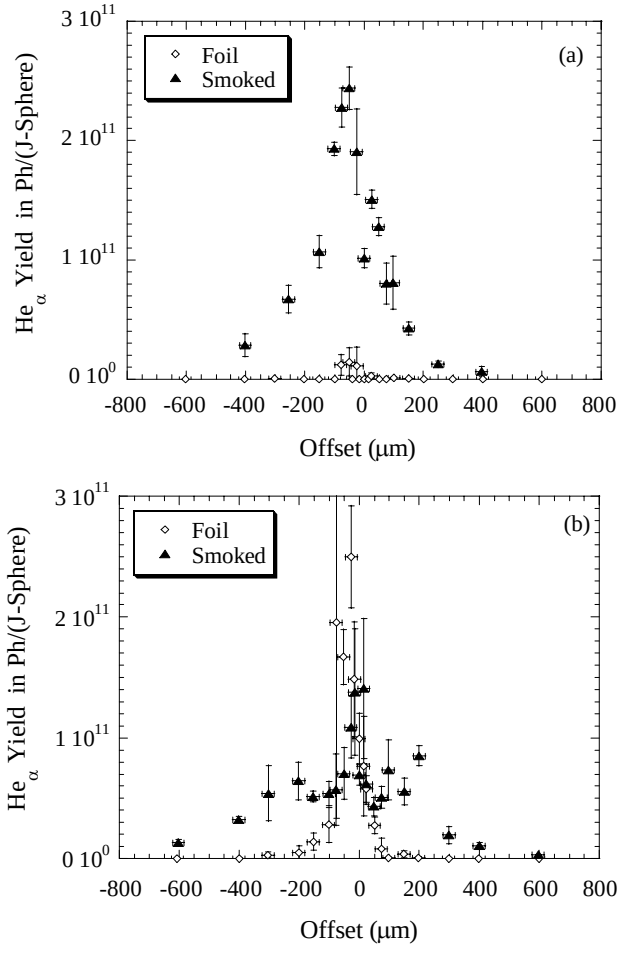

Figure 2. Integrated absolute yield of He-α as a function of offset from the best focus for foil and smoked Ti targets irradiated at 45° with (a) s-polarized and (b) p-polarized pulses. The error bars represent standard error in the yield, and fixed error of 20 μm in the offset.

The increased efficiency of p-polarisation over s-polarisation is easily understood for the foil targets. A substantially increased absorption from ~5-10% for s-polarisation[23] to over 50% is expected due to the vacuum heating mechanism[25]. In addition super-thermal electrons generated will enhance ionisation and excitation rates in the plasma for p-polarisation.

The enhancement in the yield for smoked targets, especially with s-polarisation, could be qualitatively explained in several ways. One important consideration is that the optical absorption of such targets is expected to be high (~90%). However, the absorption may also occur over a larger depth and this parameter is not well known to us at present. Also, it may be that as the randomly orientated surfaces are heated and expand they collide with each other converting kinetic energy to thermal energy and hence X-rays. The timescale for this would likely be of the order ~ps based on the size of the gaps in the structures (<400nm) and the likely expansion speeds of ~10^6m/s which is based on HYADES[26] simulations of s-polarised 45fs pulses interacting with Ti foils.

In our time integrated data, the signal is always accompanied by a uniform background covering the entire chip. Since the use of magnets and shielding did not make any difference to the level of the background, and the level varied from shot to shot depending on the focusing conditions, we surmise that the background noise on the CCD chip corresponded to hard x-ray fluorescence from the spectrometer crystal and substrate. Figure 3 shows more than an order of magnitude drop in the background level at 200μm defocus. Furthermore, there is also some indication that, even at the best focus, the level of background from the smoked targets is less compared to that from the foil targets. An added advantage of irradiating smoked away from best focus is that high He-α yield is obtained with a significant drop in hard X-ray background.

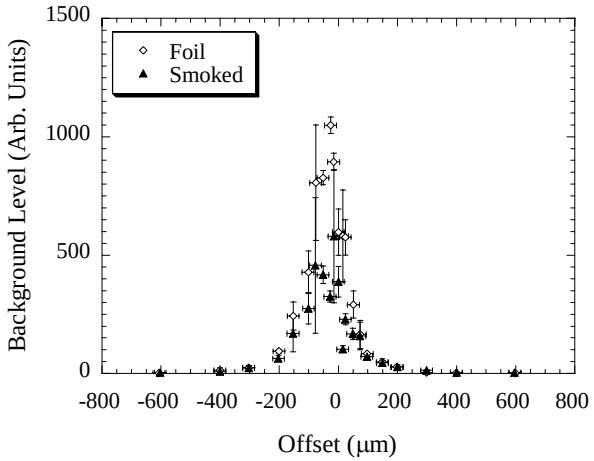

Figure 3. Comparison of the level of x-ray background generated by irradiating foil and smoked Ti target with p-polarized pulses. The error bars represent standard error in the background level and fixed error of 20 μm in the offset.

Figure 4 depicts the spectrally integrated scan of the time resolved data comparing the emission from the Ti foil and smoked target irradiated with p-polarized pulses. The spectral resolution was better than 10eV. The zero on the time scale is arbitrary. Although the satellites and inter-combination line can be seen in the time-integrated spectra they are not readily discernible in the single shot streak data which is noisy due to the low signal level and in any case has a low expected dynamic range (<10). Thus, Figure 4, in effect, represents the resonance line history. The inset shows raw data of the He-α emission from a foil target, where there is an apparent shift to the blue of ~4mÅ in magnitude during the emission period. This is consistent with a blue shift due to expansion at ~$5x10^5$ m/s.

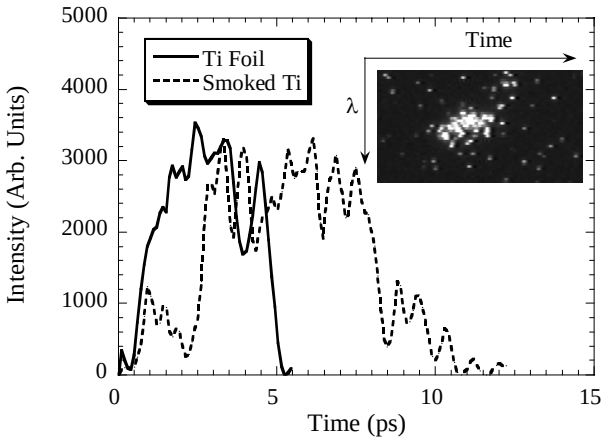

Figure 4. Spectrally integrated scans of the time resolved He-α data recorded with a Kentech streak camera coupled to a Von Hamos spectrometer employing a PET crystal. The spectral resolution was better than 10eV and the temporal resolution was ~2ps. The zero on the time scale is arbitrarily chosen. The inset is the raw streak data of He-α emission from a foil target.

The FWHM of the emission is 4ps and 5.5ps respectively for the foil and smoked target. De-convolving these times, using 2ps as the time resolution of the streak, we get 3.5ps and 5ps respectively. This shows that the duration of He-α emission from the smoked targets irradiated under the conditions discussed is not considerably longer than the emission from the foil targets. This contrasts with broad-band XUV data centred around 25nm taken with a grating spectrometer [to be published later] which indicated 50-100ps duration of emission, consistent with observations of Kulcsár *et al.*[21].

Conclusions

In conclusion, we have demonstrated that nano-structured targets can be used to significantly enhance thermal line emission from short pulse plasmas. The advantage over p-polarised irradiation of foils is less clear cut than for s-polarisation and lies more in the potential for using lower irradiance than in the maximum absolute yield. Furthermore, at 4.75keV the duration of the line emission was not significantly increased for smoked targets as it is for broad-band sub-keV energies.

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