Electron emission from atomic clusters irradiated with 10 fs laser pulses

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Introduction

The interaction of an intense (>10^{14} Wcm^{-2}), short (femtosecond) laser pulse with an atomic cluster larger than a few hundred atoms can be extremely energetic. The high local density combined with a dynamic dielectric resonance in the expanding cluster nanoplasma provides greatly enhanced coupling of the pulse to both ion and electron kinetic energies. Cluster targets can produce electron distributions in the few keV range, mean ion temperatures of 10-50 keV and peak ion kinetic energies up to 1 MeV[1]. Perhaps most significantly, clusters are also extremely efficient (> 90%) at absorbing laser light, and it is these features that have prompted the high degree of interest in this field in the last decade, in both experiment and theory[2].

We report on the first investigation of the interaction of atomic clusters with ultra-short laser pulses (< 25 fs), where the pulse duration is much shorter than the characteristic expansion time of the cluster. This allows us to investigate the initial stages of cluster heating and dynamics, well before any resonant absorption processes can occur. As expected in this regime, we find no strong dependence of peak or average ion energies on cluster size or pulse-length. The ion angular distribution is strongly anisotropic and though ion charge states higher than those expected from the monomer are produced, no energetic electrons were detected.

A weak laser prepulse can pre-form a cluster nanoplasma thus allowing the main pulse to couple with the nanoplasma more energetically[3]. The use of a prepulse is expected to be particularly important for a very short main pulse, because there is insufficient time for the cluster nanoplasma to expand to the resonant condition during the pulse. In a two pulse experiment, we show that a second few-cycle laser pulse can be used to switch on ejection of energetic (up to 500 eV) electrons, allowing a substantial amount of control over electron ejection or ‘outer ionisation’. By reducing the intensity of the prepulse to the point where it has no effect on the dynamics, we are able to measure a species-dependent threshold intensity for the pre-formation of the cluster nanoplasma.

Experimental setup

We used a 1 kHz Ti:sapphire fs laser system in Astra TA1. This system is based on hollow fibre pulse compression and produces near transform limited pulses centred at around 780 nm in the range 10-30 fs, selected by varying the degree of spectral broadening in the fibre through gas pressure and the number of chirped mirror bounces. For pulse characterisation a second harmonic generation FROG (SHG-FROG) is employed. This is simply a frequency resolved SHG autocorrelation, which yields the time versus frequency information encoded in the autocorrelation signal. A Mach-Zender type interferometer was employed for some measurements to allow the cluster source to be irradiated with two pulses. The laser was focused into a skimmed cluster beam using a 20 cm focal length 90° off-axis parabola. The average cluster size could be tuned by varying the backing pressure to the cluster beam, allowing sizes to be estimated by scaling the measurement results from previous work[4]. The

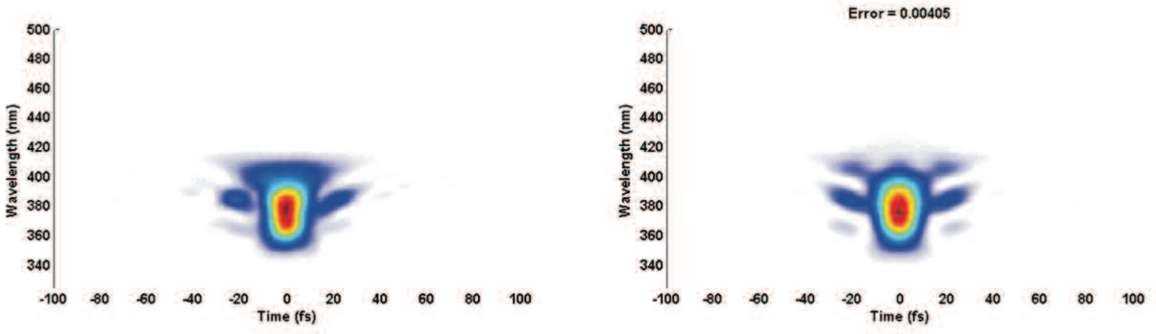

Figure 1. Experimental FROG trace (left) and retrieved trace (right), showing a 10.17 fs pulse, retrieved with a 0.41% error.

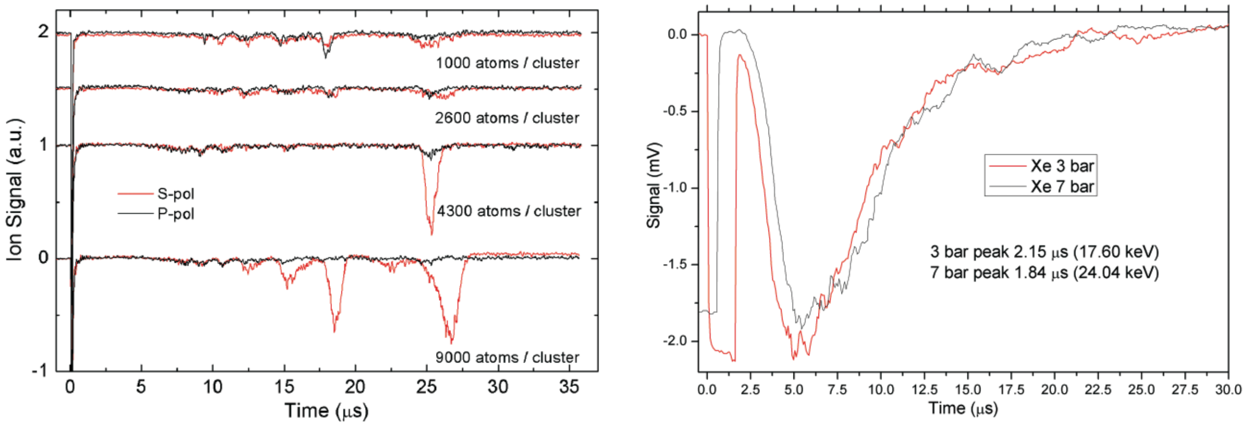

Figure 2. Time of flight traces showing asymmetry in ion emission, with increasing xenon cluster size (left). Field-free ion time-of flight trace from xenon using two pulses at optimum timing (right).

electrons and ions produced from the laser-cluster interaction with velocities perpendicular to both the cluster beam and the laser beam propagated along a flight tube and were detected by a micro-channel plate detector (MCP). The electron energies were found by measuring the decrease in MCP signal as a retarding voltage was applied to a triple grid structure placed between the interaction region and the MCP.

Results

Measured ion energies from Ar clusters from 150 to 1100 atoms and Xe clusters from 2600 to 21000 atoms irradiated with single pulses (scanned from 10 fs to 25 fs) at peak intensity of 5×10^{14} Wcm^{-2} were in the region of 100 - 500 eV. They showed no clear dependence on cluster size. The ion angular distribution was however strongly anisotropic, with the anisotropy increasing with cluster size and more ion signal detected perpendicular to the laser polarisation (figure 2). This is in contrast to measurements of more energetic ion angular distributions from clusters irradiated with longer, more intense laser pulses where the angular distribution was found to be nearly isotropic with only the highest energy ions showing some degree of anisotropy[5]. Higher ion charge states were also observed from Xe clusters, compared to those measured from the monomer. However, no electrons were observed from clusters irradiated with a single few-cycle pulse at the highest intensity available (5×10^{14} Wcm^{-2}) (figure 3a), highlighting the significance of enhancement to the electron yield achieved when using short pulse pre-heating of clusters.

In two-pulse experiments, using a 25% weak and a 75% main pulse, both of 11 fs duration, we were able to ‘switch on’ ejection of energetic electrons. The electron yield from the two-pulse scans is shown in figure 3(b). With Xe clusters, an enhancement to the signal is seen with the weak pulse both before and after the main pulse, with a peak signal increase by a factor of ~5. Retarding potentials applied indicate the electron energies achieved are up to 500 eV. Peak ion energies, measured in the same optimum position for electron emission also see a significant increase over those seen in the single pulse case, more than 10 times higher in some instances (figure 2). In each case for electron emission modeling has been shown using

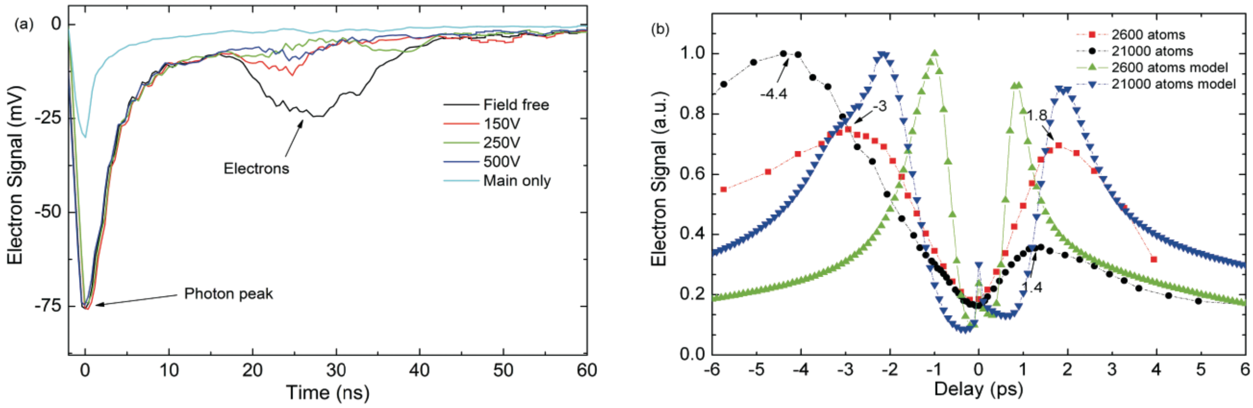

Figure 3. (a) Electron signal scans (arb units) for Xe (2600 atoms) with the main pulse alone and a 25% prepulse at -3 ps. (b) Two-pulse delay scans of 2600 and 21000 atoms Xe clusters. Negative delay indicates the weak pulse arrives at the interaction first. Theoretical results are shown for both cases using nanoplasma model.

uniform density nanoplasma theory (figure 3(b)). Cluster size distribution effects were taken into account, giving results that show good qualitative agreement, if not quantitative. The model shows similar trends in terms of the enhancement to yield in both cases, however it predicts that the peak times where these occur should be earlier.

In the case of Ar, the scans show no enhancement to electron yield when the weak pulse (4×10^{13} Wcm^{-2}) arrives before the main pulse (1×10^{14} Wcm^{-2}), however where the main pulse arrives first, a peak enhancement by a factor of ~2 is observed. The lack of signal enhancement shown in the case of Ar can be explained when taking into account the main and weak pulse intensities, and the over-the-barrier (OTB) ionisation threshold of Ar (2.5×10^{14} Wcm^{-2}). The data indicates the weak pulse used was too weak, not producing any significant ionisation or pre-formation of a nanoplasma, hence no signal enhancement. From these results, prepulses with an intensity < ~1/3 atomic OTB threshold are seen to have a negligible effect. This quantification of a species-dependent threshold intensity will be useful for cluster experiments at much higher intensities, where even a small amount of prepulse can dramatically change the explosion dynamics.

In conclusion, we have investigated the interaction of clusters with few cycle laser pulses for the first time. This has allowed us to explore the initial stages of cluster heating and dynamics. While ion charge states and energies indicate that energy is deposited into the clusters with single, few cycle laser pulses, no energetic electrons appear to be produced.

We have shown that a second few-cycle laser pulse can be used to switch on ejection of energetic (up to 500 eV) electrons, allowing a substantial amount of control over electron ejection. A similar effect is seen in ion emission while using two pulses, peak energies seen to be increased by an order of magnitude. By reducing the intensity of the pre-pulse to the point where it has no effect on the dynamics, we are able to measure a species-dependent threshold intensity for the preformation of cluster nanoplasma. Further work will see this investigation continue to smaller clusters and higher laser intensities.

References

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