Evaluation of laser-irradiated Ar clusters as a source for time-resolved x-ray studies

Larsson, Jörgen; Sjogren, A

Published in:
Review of Scientific Instruments

DOI:
10.1063/1.1149748

1999

Link to publication

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Evaluation of laser-irradiated Ar clusters as a source for time-resolved x-ray studies

J. Larsson and A. Sjögren
Department of Physics, Lund Institute of Technology, S-221 00 Lund, Sweden

(Received 14 December 1998; accepted for publication 2 February 1999)

We have measured the absolute average photon flux, the spectral characteristics, and the time structure of x rays emitted from Ar clusters which were irradiated by a 100 fs laser with an intensity of $10^{17}$ W/cm$^2$. The measured photon flux was $10^7$ photons per shot in the $K_\alpha$ (at 3 keV) line in a $4\pi$ sr solid angle. The temporal structure was measured using a streak camera with a 10 ps time resolution. It was found that less than 1% of the photons were emitted within the 10 ps time-response function of the streak camera. The emission profile is roughly exponential with a time constant of 3 ns. © 1999 American Institute of Physics [S0034-6748(99)03605-9]

I. INTRODUCTION

Over the last five years, high-intensity laser-irradiated van der Waals clusters have been the object of intense study.1–11 The high average x-ray flux gives reason for optimism when it comes to using laser-irradiated clusters as a source for relatively hard x rays (>1 keV). Possible application fields are lithography12 and x-ray microscopy. The interaction of intense laser radiation with clusters is now well understood through a model first described by Ditmire et al.4 In this model each cluster is treated as a small plasma ball, a few nanometers in size. Therefore the model is sometimes called the nano-plasma model. The model can be used to predict measurable features such as electron spectra, ion spectra, and the scaling of the emitted x-ray intensity with laser pulse duration and laser wavelength.

Since the clusters in many of the studies are irradiated with short-pulse lasers (100 fs), the time structure of the x-ray emission has been a topic of discussion. Short-time emission (<1 ps) would be of particular interest for ultrafast visible pump/x-ray probe experiments. Such studies are currently being performed with a wide range of x-ray sources such as synchrotrons where the temporal characteristics are modified with short laser pulses (<100 fs),13 laser/electron beam interactions,14 and laser-produced plasmas from solid targets.15,16

Compared to synchrotrons and electron beam devices, the laser-based sources are cheap and compact. Compared to solid target x-ray sources or solid cluster targets such as gold black,17 rare gas clusters produce little debris,18 are easily renewable and are less sensitive to alignment. All of this is important for application purposes. Many of the above mentioned advantages are also true for liquid targets.19,20 However, few experiments using short laser pulses (<1 ps) to produce x-ray emitting plasmas from liquid targets have been carried out21 and the temporal structure of the emission has yet to be studied.

In the present study, we investigate the temporal struc-
nozzle allowing for backing pressures up to 80 atm was used. The diameter of the nozzle opening was 0.8 mm. The extent of clustering in an expanding gas jet can be estimated through the so-called Hagena parameter. It is given by the semiempirical formula
\[ \Gamma^* = k \times \left( \frac{d}{\tan \alpha} \right)^{0.85} \times \rho_0 / T_0^{2.29} \]

The units for different parameters are the ones given below.

The empirical constant \( k = 1700 \) for Ar. The nozzle diameter was 500 \( \mu \)m, the pressure was 80 000 mbar. The temperature was 300 K and the cluster half angle was 15° yielding \( \Gamma^* = 2 \times 10^6 \). For this Hagena parameter a cluster size of \( 10^5 - 10^6 \) is expected. The onset of cluster formation was experimentally studied through the intensity of Rayleigh scattered light versus backing pressure. The same laser was used for the comparison study. The intensity of the scattered radiation was measured to \( 10^{11} \) W/cm\(^2\) and the scattered radiation was imaged onto a charge coupled device (CCD) chip. From the angular acceptance of the imaging lens and the number of electrons generated on the CCD chip the total number of scattered photons were estimated. The Rayleigh scattering cross section is
\[ \frac{dS}{d\Omega} = 2 \times \pi \times r^6 / \lambda^4 \times (n^2 - 1) / (n^2 + 2) \text{cm}^2 / \text{sr} \]

We observed 30 000 photons in a \( 1 \times 10^{-5} \) sr solid angle using a detector with 50% quantum efficiency. Inserting the refractive index of solid argon \( (n=1.38) \) and \( \lambda=800 \) nm yields a cluster size of 15 nm given a gas density of \( 10^{19} \) atoms/cm\(^3\). This cluster size corresponds to about \( 10^5 \) atoms/cluster atoms per cluster taking the inter-atomic spacing to be the same as in solid argon. The gas density was estimated from a measurement of the rise of static pressure in the volume of the vacuum chamber for a fixed number of gas puffs. The duration of the gas puff was estimated through the Raleigh scattering experiment.

The streak camera cathode had an estimated 3% quantum efficiency and an acceptance angle of about 3 \( \times 10^{-6} \) sr. Hence, the recorded x-ray emission was weak in the time-resolved measurements. The strongest x-ray emission was obtained using the highest backing pressure (80 bar), giving the largest clusters \( (10^5 \text{ atoms/cluster}) \) and the highest density \( (10^{19} \text{ atoms/cm}^3) \). These numbers are accurate to the order of magnitude.

The x-ray detectors were put behind filters in order to suppress stray light and soft x-ray emission. Two types of filters were used. Either a 6 \( \mu \)m thick Al filter or a combination of 6 \( \mu \)m Al and 140 \( \mu \)m plastic film. We measured the x-ray energy spectrum using a Peltier-cooled CCD camera using the fact that the number of electrons produced and stored in each CCD pixel corresponds to certain photon energy (3.6 eV/electron). The CCD chip was back thinned giving >90% quantum efficiency for 3 keV radiation. The x-ray temporal structure was measured with a commercial streak camera with a 120 nm thick solid density CsI photo cathode.

III. RESULTS AND DISCUSSION

The spectrum is shown in Fig. 2. As can be seen, the \( K_\alpha \) edge from the Al filter is clearly visible in the thermal background radiation. The smearing of this edge compared to the calculated filter response (also shown in Fig. 2), yields an estimate of the spectral resolution to about 200 eV. From the average number of photons per pulse we determine the absolute flux of Ar \( K_\alpha \)-shell radiation to be \( 10^7 \) photons per pulse at 10 Hz in a 4\( \pi \) sr solid angle.

As seen in Fig. 2, a substantial amount of the radiation originated from the continuous background with temporal emission characteristics that might differ from the line emission. In order to filter out the thermal radiation, a plastic filter was inserted. The emission spectrum as detected behind this filter combination is shown in Fig. 3. The spectrum is clearly dominated by the \( K_\alpha \)-shell emission. From the recorded spectra we estimate that 50% of the radiation arriving at the detector came from emission near the \( K_\alpha \) line. The rest was emission near the \( K_\beta \) line radiation and incoherent bremsstrahlung. Multiple pulses had to be accumulated to get sufficient photon statistics.

In Fig. 4 we show the emission characteristics over several nanoseconds. The data consist of 100 accumulated pulses. This recording was made using the slowest sweep of

![FIG. 1. Experimental setup.](Image)

![FIG. 2. Emission spectrum (solid line) as observed behind a filter. The photon count has not been modified to account for the filter transmission profile (dotted line).](Image)
the streak camera (700 ps/mm). The streak camera response to a 100 fs pulse obtained by frequency tripling of the 800 nm laser is also shown. The temporal response is limited by the slit size as well and the trigger jitter.

The remedy for the influence of the slit size was to increase the sweep speed, this, however, made the signal appear substantially weaker. To avoid trigger jitter in the accumulation, a timing fiducial, obtained from the third harmonic of the 800 nm laser and a photon-counting algorithm, was used. The principle for this technique is described in Ref. 24. However, the temporal resolution in our study was limited by the fact that already at a sweep speed of 30 ps/mm, we found that few photons arrived within the window of detection. A recording of 500 averaged shots at this sweep speed is shown in Fig. 5.

The long duration of the x-ray emission indicates that cooling predominantly occurs through expansion of the cluster, as three-body recombination is expected to show a faster time dependence. 4

Due to flux limitations, it was not possible to use a high resolution crystal spectrometer in combination with a temporally resolving detector. Although the filter could make the K-shell emission dominate the spectrum, we were not able to resolve emission from the different charge states, which, due to different screening potential, would be separated in wavelength.

From our measurements, we cannot rule out that x rays from highly ionized Ar ions are emitted during a shorter time than the average. Recombination could quench the emission from high charge states. An interesting experiment that would enable the measurement of the emission duration from different charge states would be to use time-resolved x-ray diffraction. The monochromator crystal would then be melted by a short pulse laser with a variable delay relative to the x rays. The emission from different ionization stages would be spatially separated on a position sensitive detector. The temporal structure of the emission could be deduced from the registered intensity as function of optical delay in a cross-correlation measurement similar to that described in Refs. 13 and 15. However, to successfully carry out such an experiment, a higher x-ray flux must be obtained.

We find that, although x-ray radiation from nano-plasma clusters shows promise for time-integrated applications, the long pulse duration prevents time-resolved probing of ultrafast processes.

ACKNOWLEDGMENTS

This project was supported by the Swedish Natural Science Research Council. This study was carried out at the Lund High-Power Laser Facility. The support to this facility from the Knut and Alice Wallenberg Foundation is gratefully acknowledged. The authors would like to thank Dr. Anders Persson for assisting us in operating the laser and in measuring the pulse contrast using the streak camera.

8 T. Ditmire, P. K. Patel, R. A. Smith, J. S. Wark, S. J. Rose, D. Mi-