Time-resolved Thomson scattering on high-intensity laser-produced hot dense helium plasmas

P Sperling, T Liseykina, D Bauer and R Redmer
Institut für Physik, Universität Rostock, D-18051 Rostock, Germany
E-mail: philipp.sperling@uni-rostock.de

New Journal of Physics 15 (2013) 025041 (13pp)
Received 31 August 2012
Published 27 February 2013
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/2/025041

Abstract. The introduction of brilliant free-electron lasers enables new pump–probe experiments to characterize warm and hot dense matter states, i.e. systems at solid-like densities and temperatures of one to several hundred eV. Such extreme conditions are relevant for high-energy density studies such as, e.g., in planetary physics and inertial confinement fusion. We consider here a liquid helium jet pumped with a high-intensity optical short-pulse laser that is subsequently probed with brilliant soft x-ray radiation. The optical short-pulse laser generates a strongly inhomogeneous helium plasma which is characterized with particle-in-cell simulations. We derive the respective Thomson scattering spectrum based on the Born–Mermin approximation for the dynamic structure factor considering the full density and temperature-dependent Thomson scattering cross section throughout the target. We observe plasmon modes that are generated in the interior of the target and study their temporal evolution. Such pump–probe experiments are promising tools to measure the important plasma parameters density and temperature. The method described here can be applied to various pump–probe scenarios by combining optical lasers, soft x-rays and hard x-ray sources.

1 Author to whom any correspondence should be addressed.
1. Introduction

Matter at high energy densities occurs in extreme conditions of pressure and/or temperature as relevant for astrophysics, e.g. in the deep interior of planets, in brown dwarfs or in stars [1–3]. Another important example is the concept of intertial confinement fusion, which relies on the full understanding and control of cryogenic deuterium-tritium capsules driven to high energy densities by powerful lasers as used at the National Ignition Facility in Livermore [4] or, in the near future, at the Laser Megajoule near Bordeaux; for a review, see [5].

Such extreme states of matter can be generated using various techniques. For instance, high-energy particle beams (e.g. heavy-ion beams at GSI Darmstadt) or intense short-wavelength radiation from free electron lasers (FELs, e.g. FLASH Hamburg, LCLS Stanford, Elettra Trieste and SACLA Kobe), which are brilliant soft or hard x-ray radiation sources, can be used to heat targets volumetrically. In contrast, optical lasers penetrate only into a thin surface layer (skin depth) of the target. The solid-density plasma that is generated due to rapid tunneling ionization acts as a mirror for optical wavelengths. The electrons can gain relativistic energies in the laser pulse and induce important processes in the plasma such as impact ionization and bremsstrahlung [6–8]. With the planned installation of new high-energy and ultra-short-pulse laser facilities such as the Extreme Light Infrastructure, intensities up to $10^{24} \text{W cm}^{-2}$ will be accessible in the near future. These intensities enable the production of hot dense matter (HDM) with densities close to solid density up to compressed matter well above solid density, but with electron temperatures $T_e$ above 100 eV and hence above the warm dense matter regime.

The investigation of such plasmas requires probe lasers that operate at frequencies higher than the plasma frequency $\omega_{pe}^2 = n_e e^2 / (\epsilon_0 m_e)$ of the free-electron subsystem, with the free-electron density $n_e$ and the electron mass $m_e$. Therefore, efficient x-ray sources with high brightness are inevitable for probing plasmas with densities at solid or even higher densities. Energetic optical lasers such as Omega (Rochester), Gekko (Osaka), Titan (Livermore), Vulcan (RAL) or Phelix (Darmstadt) can be used to generate intense but incoherent x-ray radiation. Alternatively, FELs provide brilliant and coherent radiation for such purposes. The FLASH in Hamburg [10, 11] operates in the soft x-ray region, while the LCLS in Stanford and the future European XFEL in Hamburg yield hard x-ray radiation. Simultaneously, x-ray Thomson scattering is a promising tool for the diagnostics of dense strongly correlated plasmas [9] in the HDM region. Therefore, this technique is already implemented at the Matter in Extreme
Conditions (MEC) instrument at LCLS and will be installed at the high energy density (HED) matter experiments instrument at the future XFEL in Hamburg.

Collective x-ray Thomson scattering experiments yield information on the density and temperature of dense plasmas [12]. For a homogeneous density and temperature profile throughout the target, these parameters can be determined directly from the plasmon dispersion and the ratio of the plasmon amplitudes via the detailed balance relation [13]. For laser frequencies below the plasma frequency for solid targets, i.e. optical lasers and energies of about 25–30 eV accessible with FLASH, the target is overdense and the absorption is limited to the skin depth, whereas the excitation by high-frequency FEL radiation generates smoother gradients [14]. The scattering signal represents an average of the local density- and temperature-dependent scattering cross sections weighted with the respective density and temperature profiles [15], which are generated not only by the pump pulse but also by the probe pulse if intense x-ray radiation pulses are used as in the case of the FLASH and LCLS facilities. Therefore, a consistent treatment of the light–matter interaction within pump–probe experiments is crucial for the determination of the plasma density and temperature, their profiles throughout the target and their temporal evolution. Furthermore, the electron–ion equilibration rate can be extracted from the Thomson scattering spectrum by varying the time delay between the pump and probe pulses.

The derivation of an inhomogeneous Thomson scattering signal weighted with the respective density and temperature profiles was shown earlier by Thiele et al [16], who investigated the averaged Thomson scattering signal of an inhomogeneous hydrogen plasma produced by an optical laser of wavelength $\lambda = 800 \, \text{nm}$ and intensity $I = 10^{15} \, \text{W cm}^{-2}$. The temporal evolution of a set of plasmon pairs characterizing different regions of the droplet could be monitored. These plasmon pairs stem from the warm dense droplet front generated by the optical laser, whereas a non-collective scattering signal representing the cold interior of the droplet was found to be caused by the FEL.

The goal of the present paper is to demonstrate the capacity of x-ray Thomson scattering experiments for HED studies. Furthermore, the role of inhomogeneities that cannot be avoided in laser–matter interaction on ultra-short time scales is investigated by using small helium droplets as the target material. For this purpose, we study here the interaction of helium droplets with a high-intensity short-pulse laser at medium to high intensities of $I = 10^{15}$, $10^{18}$ and $10^{19} \, \text{W cm}^{-2}$, which generates HDM in different regimes. The x-ray Thomson scattering spectra are calculated in order to test whether the corresponding plasma parameters can be extracted from them.

2. Theory for the dynamic structure factor

We start with the scattered power per solid angle $d\Omega = \sin \theta \, d\theta \, d\phi$ and per unit frequency interval $d\omega$ which is experimentally accessible and given by the following expression [15]:

$$\frac{d^2 P_{sc}}{d\Omega d\omega} = \frac{\sigma_T}{A_{rad}} k_i \int_{-\infty}^{\infty} \frac{d\omega'}{2\pi} G_{\Delta \omega}(\omega - \omega') \int dr \, l(r) S_{\omega c}(k, \omega'; T(r), n(r)) \, n_e(r). \quad (1)$$

Here, $\sigma_T = 6.65 \times 10^{-24} \, \text{cm}^2$ is the Thomson scattering cross-section, $k_i$ and $k_f$ are the initial and final photon wavenumbers, and the energy and momentum transfer are given by $\Delta E = \hbar \omega = \hbar \omega_f - \hbar \omega_i$ and $\Delta \mathbf{k} = \hbar \mathbf{k}_f - \hbar \mathbf{k}_i$. The central quantity for the determination of the scattering signal

New Journal of Physics 15 (2013) 025041 (http://www.njp.org/)
is the dynamic structure factor (DSF) $S_{ee}(k, \omega)$, which can be calculated for given profiles of electron density $n_e(r)$, electron temperature $T_e(r)$, ion density $n_i(r)$ and ion temperature $T_i(r)$, i.e. for the general case of an inhomogeneous target. The momentum transfer is related to the scattering angle $\theta$ in the limit $\hbar \omega \ll \hbar \omega_0$ according to $k = 4\pi \sin(\theta/2)/\lambda_0$, with $\lambda_0$ being the probe wavelength. $l(r)$ is the $r$-dependent power density of the probe beam taking into account absorption in the and target, $A_{\text{rad}}$ is the irradiated surface of the target. The DSF has to be convoluted with the instrumental function $G_{\Delta \omega}(\omega)$ that models the spectrometer’s finite spectral resolution as well as the probe’s spectral bandwidth. Usually, a normalized Gaussian distribution is employed with the full-width at half-maximum (FWHM) $\Delta \omega$.

The DSF can be written in terms of free–free, bound–free and bound–bound correlations as proposed by Chihara [17, 18]:

$$S_{ee}(k, \omega) = Z_{\text{free}} S_{ee}^0(k, \omega) + |f_i(k) + q(k)|^2 S_{ii}(k, \omega) + Z_c \int_{-\infty}^{\infty} d\omega' S_e(k, \omega) S_e(k, \omega - \omega').$$  \hspace{1cm}(2)

Here, $Z_{\text{free}} = n_e / n_i$ is the ionization degree of the plasma and $Z_c$ is the averaged number of core electrons. The three terms in equation (2) are discussed below.

In this paper, we consider the contribution of free electrons $S_{ee}^0(k, \omega)$ (the first term in equation (2)), which is connected with the longitudinal dielectric function $\epsilon(k, \omega)$ via the fluctuation–dissipation theorem

$$S_{ee}^0(k, \omega) = -\frac{\epsilon_0 \hbar^2 k^2}{\pi e^2 n_e} \text{Im} \frac{\epsilon^{-1}(k, \omega)}{1 - \exp \left( \frac{-\hbar \omega}{k_B T_e} \right)}.$$  \hspace{1cm}(3)

Considering free electrons without interactions the dielectric function is given by the random phase approximation (RPA) for the one-component plasma. Including interactions between the particles in the plasma via the dynamic electron–ion collision frequency $v(\omega)$ [19], the more general approach of Mermin [20] can be applied to the dielectric function, which then reads

$$\epsilon^M(k, \omega) - 1 = \frac{(I + i \frac{v(\omega)}{\omega}) [\epsilon^{\text{RPA}}(k, \omega + i v(\omega)) - 1]}{I + i \frac{v(\omega)}{\omega} \frac{\epsilon^{\text{RPA}}(k, \omega + iv(\omega)) - 1}{\epsilon^{\text{RPA}}(k, 0) - 1}}.$$  \hspace{1cm}(4)

Calculating the electron–ion collision frequency in Born approximation defines the Born–Mermin approximation (BMA) [13, 21–23].

A further analysis of the DSF for free electrons and the Thomson scattering process on free electrons is possible via the scattering parameter $\alpha = \kappa_e / k$, which relates the inverse screening length $\kappa_e$ (given below) to the wavenumber $k$. For $\alpha < 1$ the scattering is non-collective and we can investigate short-range correlations, while long-range correlations are relevant for collective scattering ($\alpha > 1$). In the case of long-range correlations, the DSF $S_{ee}^0(k, \omega)$ shows two particularly pronounced side maxima which are located symmetrically relative to the central ion feature described by the second term of equation (2). These peaks are directly related to the free electron density via the plasmon frequency [12, 13, 21].

For the calculation of the second term in the Chihara formula (2) which characterizes the scattering on bound electrons, we use the atomic form factor $f_i(k)$ [24] and the simple Debye–Hückel ion–ion structure factor for point charges [25]

$$S_{ii}(k) = \frac{k^2 + \kappa_i^2}{k^2 + \kappa_i^2 + \kappa_e^2}.$$  \hspace{1cm}(5)
with the inverse screening length \( \kappa_c = \sqrt{e_c^2 n_c/(\epsilon_0 k_B T_c)} \) for species \( c = e \) (electrons) and \( c = i \) (ions). In the Debye–Hückel picture, the screening cloud can be given with the electron–ion structure factor by

\[
q(k) = Z_{\text{free}} S_{ei}(k)/S_{ii}(k) = Z_{\text{free}} \kappa_c^2/(k^2 + \kappa_c^2).
\]

For the last term in equation (2), the contribution of bound–free transitions \( S_c \), we use the formalism of Schumacher et al [24, 26]. This part describes Raman-type transitions of inner shell electrons to the continuum which are modulated by the ion motion contained in \( S_s(k, \omega) \) [27]. Here, this contribution is to be neglected for the relevant energy range of −10 to 10 eV, where the Thomsons scattering signal of free electrons can be obtained.

3. Plasma generation in helium droplets

As a proposal for future experiments on inhomogeneous HDM states, we describe in this section the interaction between cryogenic helium droplets and a high-intensity short-pulse optical pump laser with different intensities. We consider for this purpose helium droplets of \( d = 6.4 \, \mu m \) diameter at an initial temperature \( T_{\text{ini}} = 20 \, K \) and density \( n = 2.2 \times 10^{22} \, cm^{-3} \). The profiles of electron temperature and density generated in the strongly inhomogeneous helium plasma are simulated with a particle-in-cell (PIC) code [28], where field ionization processes are included via a tunnel ionization rate [29]. The setup of the pump–probe experiment on the helium droplet is illustrated in figure 1.

3.1. A pump laser with an intensity of \( 10^{15} \, W \, cm^{-2} \)

First, we consider a linearly polarized optical laser pulse of wavelength \( \lambda = 800 \, nm \), pulse duration \( t_{\text{FWHM}} = 30 \, fs \), energy \( E = 3.2 \, \mu J \) and focal spot diameter \( d_{\text{FWHM}} = 3 \, \mu m \) which irradiates a helium droplet. We apply the corresponding intensity of \( 10^{15} \, W \, cm^{-2} \) in order to compare with the previous results for hydrogen given by Thiele et al [16]. Note that we use here a three orders of magnitude smaller laser energy than that in [16]. To investigate the interaction of the optical laser with the helium droplet, a PIC simulation in a cubic box of \( 8 \times 8 \times 8 \, \mu m^3 \) size was performed for a duration up to \( t = 400 \, fs \) after the maximum of the optical pump laser pulse. Such long simulation times are necessary to obtain an equilibrated system for the temperature determination. We used \( 500 \times 500 \times 500 \) grid cells with 64 heavy particles each.
The resulting profiles for the electron temperature and the ionization degree are shown in figure 2 for the laser polarization plane at $t = 400$ fs after the maximum of the pump laser pulse. Here, a weakly ionized droplet front of several 10 nm thickness comparable to the skin depth is observed. Compared to the work of Thiele et al [16] for hydrogen a less ionized and less extended plasma front is obtained for helium, which is due to the reduced laser energy and the higher ionization potential of helium atoms. The temperature is determined on a reduced grid of $50 \times 50 \times 50$ cells and adjusted to a Maxwell–Boltzmann statistics via the particle energies.

3.2. A pump laser with an intensity of $10^{18}$ W cm$^{-2}$

To observe a higher ionized plasma we consider the laser–droplet interaction with a more intense laser pulse of 3.2 mJ energy and 30 fs duration so that the intensity is $10^{18}$ W cm$^{-2}$. These laser parameters are close to the relativistic regime where the ionized electrons reach relativistic velocities. Such a laser is currently not available at FLASH, but for future experiments at the XFEL in Hamburg or at LCLS in Stanford (where a corresponding short-pulse laser is already installed in the MEC instrument) such setups would be possible. Again the simulation is performed in a cubic box of $8 \times 8 \times 8$ $\mu$m$^3$ size on $500 \times 500 \times 500$ grid cells with 64 heavy particles each for a duration up to a time of $t = 440$ fs after the maximum of the optical pump laser pulse.

The resulting profiles of the ionization degree are shown in figure 3 for three spatial planes at $t = 80$ fs after the maximum of the pump laser pulse: the laser polarization plane, the $x$–$z$ plane perpendicular to the laser polarization plane and the $y$–$z$ plane perpendicular to the laser axis as illustrated in figure 1. The results for the different planes through the droplet center indicate an inhomogeneous, asymmetrical ionization along the laser axis. In the $x$–$z$ plane perpendicular to the laser polarization plane, we obtain an overcritical, highly ionized front of several tens of nm thickness. In addition, in the polarization plane in the interior of the droplet an ionized plasma is observed due to the penetration of the laser into the droplet. This effect can
Figure 3. Profile of ionization degree $Z_{\text{free}}$ for different planes through the droplet center at a time of $t = 80\,\text{fs}$ after the maximum of the optical pump laser pulse with an intensity of $10^{18}\,\text{W}\,\text{cm}^{-2}$ and an energy of $3.2\,\mu\text{J}$. Illustrated are (a) the laser polarization plane, (b) the $x$–$z$ plane perpendicular to the laser polarization plane and (c) the $y$–$z$ plane perpendicular to the laser axis. The optical laser has irradiated the droplet from the left along the $x$-axis. We obtain an asymmetric ionization of the droplet which is caused by a focused penetration of the laser into the droplet. The effect may be understood using Mie theory [30].

be understood in terms of an enhanced electric field at the droplet surface (as predicted by Mie theory) and a plasma wave propagating from there into the target, ionizing also the interior of the droplet; this is investigated in more detail in [30].

For the calculation of Thomson scattering spectra via the BMA temperature and density profiles throughout local thermal equilibrated droplets are necessary. Therefore, results for a substantially longer time $t = 440\,\text{fs}$ after the maximum of the pump laser pulse are illustrated in figure 4. Here, the ionization degree is given for the laser polarization plane and the plane perpendicular to the laser axis on the left side of figure 4. The corresponding electron temperature profiles were derived from a reduced grid of $50 \times 50 \times 50$ boxes, see the right side of figure 4. For such longer times we observe a highly ionized droplet front and, in contrast
Figure 4. The ionization degree $Z_{\text{free}}$ (left) and electron temperature $T_e$ (right) for different droplet planes at a time of $t = 440$ fs after the pulse maximum. Illustrated are (a) the laser polarization plane and (b) the $x-z$ plane perpendicular to the polarization plane. The optical laser of intensity $10^{18}$ W cm$^{-2}$ irradiates the droplet from the left along the $x$-axis. For this time, we observe an almost homogeneously ionized interior of the droplet with a thin highly ionized front at the surface. Here, we assume an equilibrated system, where a slight decrease of the electron temperature from the front surface to the back surface of the droplet is observed.

to shorter times of $t = 80$ fs, a more homogeneous interior of the helium droplet. The focusing effect obtained for shorter times is still visible in the droplet front. The temperatures show a decrease of several hundreds of eV from the droplet front to the back of the droplet.

3.3. A pump laser with an intensity of $10^{19}$ W cm$^{-2}$

As a third case, we study a pump laser with an even higher intensity of $10^{19}$ W cm$^{-2}$ and an energy of 32 mJ. Due to this high intensity an emission of ions and electrons from the droplet is expected. Therefore, we used a bigger simulation box of $8 \times 18 \times 18 \mu$m$^{-3}$ size on
Figure 5. Profiles of (a) ionization degree $Z_{\text{free}}$ for two different droplet planes at a time of $t = 50$ fs after the pulse maximum and (b) ionization degree $Z_{\text{free}}$ and electron temperature $T_e$ at a time of $t = 90$ fs after pulse maximum. The optical laser irradiates the droplet from the left along the $x$-axis. In this case of a laser energy 32 mJ and intensity $10^{19}$ W cm$^{-2}$ a high ionization of the droplet is observed.

500 × 1125 × 1125 grid cells with 64 heavy particles per cell. In this way boundary effects are avoided but the simulation time is substantially increased. Hence, the laser–matter interaction and thereby the ionization degree profile could so far be simulated only up to 90 fs after the laser pulse maximum; the results are shown in figure 5. In contrast to the simulation of the laser–matter interaction with intensities of $10^{18}$ W cm$^{-2}$, an accelerated focused laser penetration into the droplet is observed. This can be explained by the increased laser intensity, which generates faster electrons penetrating the droplet. Moreover, a higher ionization degree at the front as well as the interior of the droplet is obtained due to the higher laser energy.

4. Thomson scattering

We have calculated the overall Thomson scattering spectrum of the helium droplet via the BMA according to section 2 for a probe laser wavelength of $\lambda_0 = 13.5$ nm. We use the plasma parameter profiles from the PIC simulations with a laser intensity of $10^{18}$ and $10^{19}$ W cm$^{-2}$, which are illustrated in figures 4 and 5. For the lower intensity of $10^{15}$ W cm$^{-2}$ the plasmon signal is very weak because of the low degree of ionization is and completely concealed by the
ion feature. In the following, the ion density is fixed at the initial density, the ion temperature is assumed to be equal to the electron temperature and a normalized Gaussian distribution function with the FWHM $\Delta \omega = 1$ eV as the instrumental function is employed. For the BMA calculation, we have used the reduced equidistant grid of $50 \times 50 \times 50$ boxes as for the determination of the electron temperature profile. The overall Thomson scattering spectrum of the helium droplet is derived as the equally weighted sum of the Thomson scattering spectra for each box. Each box is assumed to contain a homogeneous plasma, because FEL absorption effects are neglected due to the high penetration depth of the FEL and the high thermal energy in the system in comparison to the FEL energy.

The overall Thomson scattering spectrum is shown in figure 6 for a laser intensity of $10^{18}$ W cm$^{-2}$ for two different scattering angles and times $t = 190$ and 440 fs after the maximum of the pump laser pulse and for a laser intensity of $10^{19}$ W cm$^{-2}$ for one scattering angle and time $t = 90$ fs after the maximum of the pump laser pulse. On the left side of figure 6 the overall Thomson scattering spectrum is covered, whereas on the right side the plasmon peaks representing collective Thomson scattering of free electrons are shown enlarged. Here, we investigate for a scattering angle of $\theta = 90^\circ$ the non-collective and for a scattering angle of $\theta = 20^\circ$ the collective scattering regime. In addition, we observe for each time and intensity at the scattering angle $\theta = 20^\circ$, one plasmon pair which determines the dominating plasma parameters of the droplet. For a laser intensity of $10^{18}$ W cm$^{-2}$, the plasmon pair at time $t = 190$ fs at an energy shift $|\Delta E| \approx 4.25$ eV represents a plasma with an effective electron density $n_e \approx 1.3 \times 10^{22}$ cm$^{-3}$ and temperature $T_e \approx 75$ eV, whereas at time $t = 440$ fs the plasmon...
pair at an energy shift $|\Delta E| \approx 4.6\,\text{eV}$ specifies a plasma with an effective electron density $n_e \approx 1.4 \times 10^{22}\,\text{cm}^{-3}$ and temperature $T_e \approx 260\,\text{eV}$. These plasma parameters stem from the interior of the droplet and indicate an evolution of the plasma in which the HDM expands into the droplet. This behavior can also be seen in figures 3 and 4. For a laser intensity of $10^{19}\,\text{W cm}^{-2}$, the plasmon pair at an energy shift $|\Delta E| \approx 6.46\,\text{eV}$ identifies a plasma with an effective electron density $n_e \approx 2.15 \times 10^{22}\,\text{cm}^{-3}$ and temperature $T_e \approx 2030\,\text{eV}$. At a time of about 90 fs after the pump pulse maximum a similar homogeneous interior as in the case of a pump laser with an intensity of $10^{18}\,\text{W cm}^{-2}$ is observed. However, the ionization degree is in this case about unity and, therefore, two pronounced plasmon peaks are obtained at an energy of $|\Delta E| \approx 6.46\,\text{eV}$. For comparison, the Thomson scattering spectrum for a homogeneous plasma with these effective plasma parameters is illustrated for $\theta = 20^\circ$ in figure 6. Here, the plasmon peak is normalized to the maximal plasmon peak of the corresponding overall Thomson scattering spectrum. Compared to the effective Thomson scattering spectrum of the homogeneous target, we observe a broadened plasmon peak and higher values for smaller energy shifts $\Delta E$ in the overall Thomson scattering spectrum. This indicates that the plasmon pair signal consists of plasma regions with different plasma parameters, which all contribute to the overall Thomson scattering spectrum.

5. Conclusions

In this paper, we have calculated the overall Thomson scattering signal of inhomogeneous helium droplets which are pumped by a short-pulse optical laser of different intensities and probed with brilliant FEL radiation. We have obtained the density and temperature profiles for the pump phase with a $10^{15}\,\text{W cm}^{-2}$ laser at $t = 400\,\text{fs}$, a $10^{18}\,\text{W cm}^{-2}$ laser at $t = 80, 190$ and $440\,\text{fs}$ and a $10^{19}\,\text{W cm}^{-2}$ laser at $t = 50$ and $90\,\text{fs}$ after the maximum of the pump laser pulse with a PIC code. The Thomson scattering signal was derived from these density and temperature profiles only for $10^{18}$ and $10^{19}\,\text{W cm}^{-2}$ via the BMA, because for $10^{15}\,\text{W cm}^{-2}$ the plasmon pairs are concealed by the ion feature.

We have shown that the inhomogeneous ionization process in the helium droplets irradiated with a high-intensity short-pulse laser predicted for short time scales in [30] evolves in the interior of the droplet for larger time scales of several hundreds of fs to a plasma with a homogeneous ionized interior and a highly ionized front surface. The evolution of the ionized droplet interior is reflected in the resulting overall Thomson scattering spectrum of this system, where only one plasmon pair dominates. The temporal resolution of this plasmon pair characterizes the evolution of the plasma parameters throughout the helium droplet. The overall Thomson scattering spectrum shows that in contrast to hydrogen droplets irradiated with smaller intensities of $I \approx 10^{15}\,\text{W cm}^{-2}$ as studied by Thiele et al [16], the Thomson scattering spectrum is not dominated by the surface of the droplet. In the present work, a plasmon pair can be resolved which stems from the interior of the droplet. The plasma is produced by an intense laser of $I \approx 10^{18}\,\text{W cm}^{-2}$ which can be provided at the MEC station at the LCLS at SLAC or in the future at the HED instrument at the XFEL in Hamburg.

Our calculations show that Thomson scattering on inhomogeneous helium droplets irradiated with high-intensity short-pulse lasers can spatially and temporally resolve the interior heating process in the HDM region. This technique can be extended by applying the calculation of the non-equilibrium DSF to derive the Thomson scattering spectrum in the short-scale heating process of the helium droplet where a strongly inhomogeneous target is observed. At these times...
separated plasmon pairs are predicted. In addition, the long-time behavior of the droplet cooling can be observed if a more-dimensional radiation-hydrodynamics code is applied, with the PIC density and temperature profiles as the input.

Acknowledgments

This work was supported by the DFG within the SFB 652 ‘Strong correlations and collective effects in radiation fields: Coulomb systems, clusters and particles’ and the Federal Ministry of Education and Science (BMBF) under grant no. FSP 301-FLASH, project no. 05KS7HRA. PIC simulations were performed with the computing resources granted by the John von Neumann-Institut für Computing under project numbers HRO01 and HRO02.

References

[1] Remington B A, Cavallo R M, Edwards M J, Ho D D-M, Lasinski B F, Lorenz K T, Lorenzana H E, Menaney J M, Pollaine S M and Smith R F 2005 Accessing high pressure states relevant to core conditions in the giant planets Astrophys. Space Sci. 298 235
[2] Fortney J J, Glenzer S H, Koenig M, Militzer B, Saumon D and Valencia D 2009 Frontiers of the physics of dense plasmas and planetary interiors: experiments, theory, and applications Phys. Plasmas 16 041003
[3] Drake R P 2009 Perspectives on high-energy-density physics Phys. Plasmas 16 055501
[4] Moses E L, Boyd R N, Remington B A, Keane C J and Al-Ayat R 2009 The National Ignition Facility: ushering in a new age for high energy density science Phys. Plasmas 16 041006
[5] Committee on High Energy Density Plasma Physics, Plasma Science Committee and National Research Council 2003 Frontiers in High Energy Density Physics: The X-Games of Contemporary Science (Washington, DC: National Academies Press)
[6] Pukhov A 2003 Strong field interaction of laser radiation Rep. Prog. Phys. 66 47–101
[7] Gibbon P 2005 Short Pulse Laser Interactions with Matter: An Introduction (Singapore: World Scientific)
[8] Mulser P and Bauer D 2010 High Power Laser–Matter Interaction (Berlin: Springer)
[9] Glenzer S H and Redmer R 2009 X-ray Thomson scattering in high energy density plasmas Rev. Mod. Phys. 81 1625
[10] Toleikis S et al 2010 Soft x-ray scattering using FEL radiation for probing near-solid density plasmas at few electron volt temperatures High Energy Density Phys. 6 15
[11] Fäustlin R R et al 2010 Observation of ultrafast non-equilibrium collective dynamics in warm dense hydrogen Phys. Rev. Lett. 104 125002
[12] Glenzer S H et al 2007 Observations of plasmons in warm dense matter Phys. Rev. Lett. 98 065002
[13] Höll A et al 2007 Thomson scattering from near-solid density plasmas using soft x-ray free electron lasers High Energy Density Phys. 3 120
[14] Nagler B et al 2009 Turning solid aluminium transparent by intense soft x-ray photoionization Nature Phys. 5 693
[15] Baldis H A, Dunn J, Foord M E and Rozmus W 2002 Thomson scattering diagnostic of solid density plasmas using x-ray lasers Rev. Sci. Instrum. 73 4223
[16] Thiele R et al 2010 Thomson scattering on inhomogeneous targets Phys. Rev. E 82 056404
[17] Chihara J 1987 Difference in x-ray scattering between metallic and non-metallic liquids due to conduction electrons J. Phys. F: Met. Phys. 17 295
[18] Chihara J 2000 Interaction of photons with plasmas and liquid metals-photoabsorption and scattering J. Phys.: Condens. Matter 12 231
[19] Selchow A, Röpke G, Wierling A, Reinholz H, Pschischul T and Zwicknagel G 2001 Dynamic structure factor for a two-component model plasma Phys. Rev. E 64 056410

New Journal of Physics 15 (2013) 025041 (http://www.njp.org/)
[20] Mermin N D 1970 Lindhard dielectric function in the relaxation-time approximation Phys. Rev. B 1 2362
[21] Thiele R, Bornath T, Fortmann C, Höll A, Redmer R, Reinholz H, Röpke G, Wierling A, Glenzer S H and Gregori G 2008 Plasmon resonance in warm dense matter Phys. Rev. E 78 026411
[22] Höll A, Redmer R, Röpke G and Reinholz H 2004 X-ray Thomson scattering in warm dense matter Eur. Phys. J. D 29 159
[23] Redmer R, Reinholz H, Röpke G, Thiele R and Höll A 2005 Theory of x-ray Thomson scattering in dense plasmas IEEE Trans. Plasma Sci. 33 77
[24] Schumacher M, Smend F and Borchert I 1975 Incoherent scattering of gamma rays by inner-shell electrons J. Phys. B: At. Mol. Phys. 8 1428
[25] Sperling P, Thiele R, Holst B, Fortmann C, Glenzer S H, Toleikis S, Tschentscher Th and Redmer R 2011 Two-color Thomson scattering at FLASH High Energy Density Phys. 7 145–9
[26] Gregori G, Glenzer S H, Rogers F J, Pollaine S M, Landen O L, Blancard C, Faussurier G, Renaudin P, Kuhlbrodt S and Redmer R 2004 Electronic structure measurements of dense plasmas Phys. Plasmas 11 2754
[27] Sahoo S, Gribakin G F, Shabbir Naz G, Kohanoff J and Riley D 2008 Compton scatter profiles for warm dense matter Phys. Rev. E 77 046402
[28] Liseykina T V, Pirner S and Bauer D 2010 Relativistic attosecond electron bunches from laser-illuminated droplets Phys. Rev. Lett. 104 095002
[29] Popov V S 2004 Tunnel and multiphoton ionization of atoms and ions in a strong laser field (Keldysh theory) Phys. Usp. 47 855
[30] Liseykina T V and Bauer D 2012 Plasma formation in intense laser–droplet interaction arXiv:1209.5948