X-ray Thomson scattering diagnostics of impact ionization in laser-driven carbon foils

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Abstract.

We have studied the light-matter interaction of ultra-short, intense optical laser fields with thin carbon foils via particle-in-cell simulations. Especially, the influence of additional impact ionization on the density and temperature of the generated plasma and on the corresponding Thomson scattering spectra was investigated which has been found essential for laser intensities $I > 10^{16}$ W/cm². We predict a pump-probe experiment at the free electron laser FLASH in order to verify the importance of this effect in the laser-matter interaction on ultra-short time scales and to check our predictions quantitatively.

1. Introduction

The study of matter at high energy densities is relevant for astrophysics, e.g., for the modeling of Jovian planets and stellar interiors [1, 2, 3], or the concept of inertial confinement fusion, where D-T fuel capsules are compressed by the most powerful lasers available today at, e.g., the National Ignition Facility in Livermore [4] or, in the near future, the Laser Megajoule near Bordeaux [5].

The preparation of extreme states at temperatures in excess of 1 eV and densities well above the usual solid state under static conditions is almost impossible. Alternatively, such states can be generated dynamically, e.g., via the interaction of a solid target with an intense short pulse of either high-energy particles or intense radiation. Here, volumetric target heating can be performed via short wavelength radiation whereas optical laser radiation penetrates only into the skin depth and, therefore, causes strongly inhomogeneous heating of the target. The inhomogeneity of the target is driven by various effects induced by the laser field, e.g. tunnel ionization [6], bremsstrahlung, wake-field generation, self-focusing [7], the Brunel effect [8], resonance absorption [9], and $\mathbf{J} \times \mathbf{B}$ heating [10], and can be simulated by 3-dimensional particle-in-cell (PIC) codes solving Maxwell's equations [11]. However, an accurate description of the laser-matter interaction and an accurate prediction of the laser-generated plasma parameters such as temperature and density, especially for high-intensity laser pulses on short time scales below 10 ps, is still missing. In particular, impact ionization, induced by free electrons that are produced via tunnel ionization in the skin depth, accelerated in the laser field and, thus, heat the interior of the target [12, 13], is an important effect for the fundamental understanding of the complex laser-matter interaction, the laser-driven generation of plasmas on ultra-short time scales [14], the excitation of clusters [15, 16], and for applications like inertial confinement fusion. Therefore, we will propose an experiment at FLASH using x-ray Thomson scattering to investigate the influence of impact ionization in the laser-matter interaction on short time scales simulated in this paper via a PIC code.

A versatile tool for the investigation of matter at high energy densities is x-ray Thomson scattering, which allows inferring the volumetric plasma properties due to the high penetration depth of the x-rays operating at frequencies higher than the plasma frequency $\omega_{pe}^2 = n_e e^2 / (\epsilon_0 m_0)$. This technique was successfully applied in the past decade in proof-of-principle experiments [17, 18, 19]. Due to the advent of Free Electron Lasers (FELs) operating at wavelengths in the x-ray regime like the LCLS, SACLA, and, in near future, the European XFEL, also highly compressed matter at densities exceeding that at ambient conditions many times can be studied. These devices have also pulse lengths on the femtosecond time scale whereby FELs are predestined for the diagnostics of the temporal evolution of plasmas generated by short-pulse laser irradiation [14, 20]. This evolution can be investigated within pump-probe experiments where an optical pump laser generates a plasma which is subsequently probed by FEL pulses with a well-defined but flexible time delay.

Experiments in the collective x-ray regime yield important information on the electronic sub-system [21]. The plasma density of homogeneous targets can be determined via the plasmon dispersion relation [22] and the temperature via the ratio between the plasmon peaks according to the detailed balance relation [23]. This method was already extended to inhomogeneous targets [24] where individual plasmon peaks appear that can be related to regions with different ionization. Corresponding pump-probe experiments were proposed for hydrogen [25] and helium droplets [26] using specific pulse shapes in order to study the temporal evolution of the inhomogeneous plasma. A similar setup is applied in this paper using thin carbon foils in order to investigate the role of impact ionization processes.

Our paper is organized as follows. We figure the implementation of impact ionization into the PIC code VLPL3D [27] via the Lotz formula [28, 29] in Sec. 2. In Sec. 3 the theory of Thomson scattering via the dynamic structure factor is briefly outlined. The influence of impact ionization on the laser-matter interaction is then studied in Sec. 4, and its impact on the corresponding Thomson scattering spectra is investigated in Sec. 5. In Sec. 6 a possible experiment at FLASH is proposed that verifies the influence of impact ionization processes theoretically predicted in this paper. Conclusions are given in Sec. 7.

2. Impact ionization model

Within this study the process of impact ionization was implemented in the PIC code VLPL3D [27] that already has been extended to include tunnel ionization processes [30]. We have chosen a Monte Carlo method [31, 32] to treat impact ionization processes in the PIC code, using the probability distribution of the j -th ionized atom $w_j = 1 - e^{-\Delta t \nu_{ei,j}}$, the time step Δt , the collision frequency $\nu_{ei,j} = n_e |\mathbf{v}_e - \mathbf{v}_i| \sigma_j$ between the electron and the j -th ionized atom, the velocity of the electron $\mathbf{v}_e$ and the ion $\mathbf{v}_i$, the electron density n_e , and the cross section of impact ionization as given by Lotz [28, 29],

$$\sigma_j = a \zeta_j \frac{\ln \frac{E_{\text{kin},e}}{I_{p,j}}}{E_{\text{kin},e} I_{p,j}}, \quad \text{with } E_{\text{kin},e} \geq I_{p,j}. \quad (1)$$

Here, ζ_j characterizes the number of electrons in the outermost sub-shell of the j -th ionized atom, a is an empirical constant given by $a = 2.6 \times 10^{-14} \text{ cm}^2 \text{ eV}^2$ [28], $I_{p,j}$ is the ionization potential of the j -th ionized atom, and $E_{\text{kin},e}$ is the kinetic energy of the incoming electron. Due to the high demand in computer resources for the 3-dimensional PIC simulations a simple ionization model is used to reduce the calculation time per electron of an overall set of up to 10^9 electrons per calculation within up to 10^4 time steps considered in this work. After the impact ionization process the colliding electron has the momentum

$$p'_e = \frac{1}{c} \left((E_e - I_{p,j})^2 - m_e^2 c^4 \right)^{\frac{1}{2}}, \quad (2)$$

with the relativistic energy $E_e = \gamma m_e c^2$, $\gamma = (1 - (\mathbf{v}_e/c)^2)^{-1/2}$. To further reduce the calculation demands the colliding electron does not change its initial direction, the

repulsion of the ion is neglected, and the released electron is assumed to be at rest. These assumptions conserve the energy. The treatment of momentum conservation as well as the applied cross section for the impact ionizations have to be improved in further work. In addition, the suppression of the ionization potential I_p via pressure effects and local fields [33, 34] was neglected and has to be addressed in future work.

3. Theory of the dynamic structure factor

In this paper, we apply x-ray Thomson scattering for the diagnostics of the plasma generated in the target due to irradiation with ultra-short optical laser pulses that drive various ionization processes. The scattered power per unit solid angle $d\Omega = \sin\theta d\theta d\varphi$ within an unit frequency interval $d\omega$ is given by [35]:

$$\frac{d^2 P_{sc}}{d\Omega d\omega} = \frac{\sigma_T}{A_{rad}} \frac{k_f}{k_i} \int_{-\infty}^{\infty} \frac{d\omega'}{2\pi} G_{\Delta\omega}(\omega - \omega') \int d\mathbf{r} l(\mathbf{r}) S_{ee}(k, \omega'; T_i(\mathbf{r}), T_e(\mathbf{r}), n_i(\mathbf{r}), n_e(\mathbf{r})) n_e^{\text{tot}}(\mathbf{r}). \quad (3)$$

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, the energy and momentum transfer are given by $\Delta E = \hbar\omega = \hbar\omega_f - \hbar\omega_i$ and $\hbar\mathbf{k} = \hbar\mathbf{k}_f - \hbar\mathbf{k}_i$. The central quantity for the determination of the scattering signal is the dynamic structure factor (DSF) $S_{ee}(\mathbf{k}, \omega)$ which can be calculated for given profiles of electron density $n_e(\mathbf{r})$, electron temperature $T_e(\mathbf{r})$, ion density $n_i(\mathbf{r})$, and ion temperature $T_i(\mathbf{r})$ [21], i.e. for the general case of an inhomogeneous target. The momentum transfer is related to the scattering angle θ in the limit $\hbar\omega \ll \hbar\omega_0$ according to $k = 4\pi \sin(\theta/2)/\lambda_0$, with λ_0 being the probe wavelength. $l(\mathbf{r})$ is the $\mathbf{r}$ -dependent power density of the probe beam taking into account absorption in the target, A_{rad} is the irradiated surface of the target, and $n_e^{\text{tot}}(\mathbf{r})$ is the total electron density including all free and bound electrons. In order to mimic realistic experimental conditions, 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) $\Delta\omega$. If the instrument is properly characterized, its measured instrument function can be used instead, frequently improving the precision of the theoretical fit to the experimental data.

The DSF can be written in terms of free-free, bound-free, and bound-bound correlations as proposed by Chihara [36, 37]

$$S_{ee}(k, \omega) = Z_{\text{free}} S_{ee}^0(k, \omega) + |f_i(k) + q(k)|^2 S_{ii}(k, \omega) + Z_c \int_{-\infty}^{\infty} d\omega' S_c(k, \omega) S_s(k, \omega - \omega'). \quad (4)$$

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 structure factor of the free electron system is given by the structure factor S_{ee}^0 which is calculated within the Born-Mermin Approximation

(BMA) [25, 26] where electron-ion collisions are included via the collision frequency derived in Born approximation [38], combined with a Mermin-like extension of the RPA dielectric function [39]. The contribution of bound electrons is given by the ion structure factor S_{ii} weighted by the form factor $f_i(k)$ of tightly bound electrons and the screening function $q(k)$ of weakly bound electrons. The screening cloud and the ion structure factor are evaluated via the Debye-Hückel theory, whereas the form factor is approximated using hydrogenic wave functions [40]. Finally, electron ionization during the scattering event is given by the bound-free structure factor $S_c(k, \omega)$ which is modulated by the ion movement S_s [41]. This contribution is calculated via the bound-free transition matrix elements using plane waves for free electrons and hydrogen wave functions for bound electrons.

4. Plasma generation in thin carbon foils

To test the influence of impact ionization on the laser-matter interaction we have simulated the plasma generation in a carbon foil with the PIC code VLPL3D. We assume an initial density $\rho = 2.26 \text{ g/cm}^3$, a temperature $T = 300 \text{ K}$, and a foil thickness of $d = 0.25 \text{ }\mu\text{m}$. The foil is pumped by an optical laser $\lambda = 800 \text{ nm}$ with an energy $E = 20 \text{ mJ}$, a pulse duration $t_{\text{FWHM}} = 100 \text{ fs}$, and a focal spot size of $d_{\text{FWHM}} = 16 \text{ }\mu\text{m}$. We perform the simulation on a box of $2.4 \times 32 \times 32 \text{ }\mu\text{m}^3$ with a grid of $120 \times 1120 \times 1120$ cells, each with 16 heavy particles and up to 96 electrons. For the investigation of the influence of the impact ionization on the laser-matter interaction, this setup is simulated with and without additional impact ionization processes. Due to the high computational demands the simulations with impact ionization are performed up to a delay time of $\Delta t = 250 \text{ fs}$, whereas for simulations neglecting impact ionization results up to a delay time of $\Delta t = 350 \text{ fs}$ can be given. In Fig. 1, the resulting profiles of the ionization degree are shown for different times after the laser pulse maximum hits the carbon foil.

The laser pulse maximum reaches the foil at $\Delta t = 0 \text{ ps}$, where at the foil surface the laser has already generated an optically thick plasma, screening the interior of the foil from direct laser irradiation. Nevertheless, electrons, accelerated in the foil surface by the laser, can penetrate deep into the target interior.

As shown in the left panels of Fig. 1 these accelerated electrons generate a highly ionized interior of the foil via impact ionization. The panels on the right show a much lower ionization degree in the interior because impact ionization is neglected. Due to the additional ionization process the foil surface shows also a higher ionization degree in the left panels of Fig. 1. For convenience, the mean ionization degree of the whole foil $Z_m = \sum_i Z_i / N$ as sum over all N grid cells indicates a higher ionization if impact ionization is included in the PIC simulations, see Fig. 1.

With the information about the kinetic energy of the electrons, provided by the PIC simulations, we are able to extract the electron temperature of the carbon foil. For a local thermal equilibrium, this can be realized via a Maxwell-Boltzmann fit for the electron probability density as function of their kinetic energy. This is illustrated in

Figure 1. (color online) Profiles of the ionization degree through the carbon foil imposed by the optical laser for a) 0 fs, b) 100 fs, and c) 250 fs after the optical laser pulse maximum has reached the carbon foil from above. The profiles are a cut through the 3-dimensional results of the PIC simulations along the laser polarization plane. In the left/right panels results with/without impact ionization are shown.

Fig. 2 and indicates an almost equilibrated electron system. To reach sufficient electron statistics for the box of the PIC simulation, neighboring cells were combined to form a grid of $16 \times 50 \times 50$ cells. For each of these cells the electron temperature was extracted that is shown in Fig. 3. Here, only results above delay times of $\Delta t = 100$ fs are presented because for shorter times no equilibrium can be warranted. In the results considering impact ionization we observe a hot front of the foil with an electron temperature of up to 50 eV, whereas the interior is heated up to only 20 eV, indicating warm electrons

accelerated into the carbon foil. For the results neglecting impact ionization, the surface as well as the interior of the target have a constant electron temperature of approximately 45 eV because the thermal energy of the electrons is not reduced due to impact ionization processes.

Figure 2. (color online) Electron probability density as function of their kinetic energy E_{kin} for the simulation with and without additional impact ionization for delay times of 100 fs and 350 fs. For convenience, only those ionization levels of carbon are indicated (dash-dotted lines) which have a higher energy than the maximum of the probability density of the electrons with impact ionization (black curve).

In addition, the differences between the electron temperature profiles for simulations with and without impact ionization are illustrated using the electron probability density dependent on the kinetic energy of a cell chosen in the heating area of the foil. The probability density for several delay times is shown in Fig. 2. In case of simulations including impact ionization the probability for the occurrence of electrons with kinetic energies below the first ionization stage of carbon is much higher compared with simulations neglecting impact ionization. The reason is that electrons with kinetic energies below the first ionization energy of carbon $I_{p,0} = 11.26$ eV do not impact-ionize the target. In addition, in the case of simulations without impact ionization, a comparison for different delay times is given, where a decrease of the electron temperature with increasing delay time is observed, caused by the electrical field interaction between particles and ions and electrons outside the Debye sphere of the particle.

Furthermore, the dependence of the carbon foil ionization on the incoming pump-laser intensity is investigated. For that purpose, additional PIC simulations with laser energies of $E = 0.2$ and 2 mJ yielding intensities of $I = 10^{15}$ and 10^{16} W/cm² have been performed. The results of the mean ionization degree Z_m in dependence on the foil depth for the different laser intensities are shown in Fig. 4. Here, the mean ionization

Figure 3. (color online) Electron temperature profiles of the optical laser-carbon foil interaction 100 fs after the laser pulse maximum has reached the carbon foil from above. The profiles are a cut through the 3-dimensional results of the PIC simulations along the laser polarization plane. In the left/right panels the results with/without impact ionization are shown.

degree Z_m indicates the mean value of the ionization integrated over the PIC simulation box of 1120×1120 cells. The influence of impact ionization on the overall of the carbon foil for intensities of $I = 10^{15}$ W/cm² and $I = 10^{16}$ W/cm² is small. However, in the case of a pump laser intensity of $I = 10^{17}$ W/cm² a much higher mean ionization degree is observed in the results including impact ionization. Therefore, the effect of impact ionization is only important for intensities above $I = 10^{16}$ W/cm².

Figure 4. (color online) Mean ionization degree Z_m in dependence on the foil depth for different pump laser intensities. The influence on the impact ionization occurs at an intensity above 10^{16} W/cm², where a significant higher ionization is observed in contrast to the case without impact ionization.

To take into account also the influence of the FLASH probe laser of an intensity of 10^{15} W/cm² with a pulse duration of 30 fs at a wavelength of 5 nm one-dimensional

radiation-hydrodynamic simulations via the code HELIOS [42] were performed. The simulations were realized for each row of cells along the laser axis for all 16×50 rows with the initial densities and temperatures as derived from the PIC code. This technique has already been used for pump-probe experiments on hydrogen droplets; for details, see [25]. The HELIOS simulations indicate that the probe laser has only a weak influence on the plasma parameters in the carbon foil by increasing the electron temperature by 10 % and the ionization degree by 2 – 5%.

5. Thomson scattering

To calculate the Thomson scattering signal for the entirely pumped carbon foil simulated via the 3-dimensional PIC code VLPL3D probed by the FLASH laser taken into account via one-dimensional radiation-hydrodynamics simulations, Eq. 3 is used. The spatial integral in Eq. 3 is evaluated as a sum over a grid of $16 \times 50 \times 50$ cells used in Fig. 3. Here, the dynamic structure factor is calculated for each cell and then weighted with the total electron density (assumed as constant) and the photon number. Notice that we have calculated the structure factor assuming local thermal equilibrium. For ultra-short times, in this paper for a delay time of 100 fs including impact ionization, slight non-equilibrium effects are obtained, see Fig. 2. These are caused by a small fraction of high-energetic electrons present in the thermalized region which will be neglected in the calculations of the Thomson scattering spectra here. A simple model that takes into account non-equilibrium effects in the calculation of the Thomson scattering spectrum has been introduced in [43].

The Thomson scattering spectra of the ionized carbon foil are calculated for a probe laser wavelength of 5 nm and scattering angles of 20° , 90° , and 160° as can be provided at FLASH or at LCLS. This probe wavelength (photon energy of 248 eV) lies well above the K-absorption edge (4.4 nm or 282 eV) and ensures that the attenuation length of $l_{\text{abs}} \sim 1.5 \mu\text{m}$ is large compared to the foil thickness of $0.25 \mu\text{m}$. Hence photo-absorption of the probe pulse in the target can be neglected. Further, the blue-shifted inelastic scattering ($\Delta E < 25$ eV, see Fig. 5), will not interfere with potentially emitted carbon $K\alpha$ radiation. As instrument function a Gaussian with 2.5 eV FWHM is applied. In Fig. 5 the results for the Thomson scattering spectra with and without impact ionization for different delay times between the pump laser with an intensity of $I = 10^{17} \text{ W/cm}^2$ and the probe laser can be seen. The Thomson scattering of the carbon foil pumped with smaller intensities are not shown here since the focus of this paper lies on the investigation of impact ionization processes, which are not relevant for pump laser intensities below 10^{16} W/cm^2 . In the calculations an equilibrium between the electron and ion temperature is assumed, which is relevant for the calculation of the scattering off bound electrons.

The Thomson scattering contribution of the free electron system can be obtained from Fig. 5. The collective Thomson scattering signal is observable for positive energy shifts up to an energy of ≈ 25 eV, whereas for negative energy shifts the signal is

Figure 5. (color online) Thomson scattering spectra dependent on the probe laser energy shift ΔE calculated from the electron temperature and density of the overall carbon foil provided by the PIC simulations. Shown are the spectra from the laser driven carbon foil with a laser intensity of 10^{17} W/cm 2 for delay times of 100 fs and 350 fs derived with and without additional impact ionization. For comparison, the Thomson scattering spectra at an angle of 160° from the laser driven carbon foil irradiated with a laser intensity of 3×10^{17} W/cm 2 derived with impact ionization is indicated in blue. This result implies smaller electron densities and temperatures in the carbon foil as can be seen in Fig. 4.

modulated by the contribution of the bound-free transitions. In addition, also non-collective Thomson scattering is present in the overall scattering signal but is dominated by the Rayleigh scattering, due to the small Compton edge shift for the wavelength of 5 nm. From the collective Thomson scattering spectrum the effective electron temperature and density of the whole foil can be deducted which are shown in Tab. 1. The effective electron temperature and density implies that in simulations with impact ionization a higher electron density and smaller temperatures of the overall target can be expected. This can also be obtained from the PIC simulations shown in Fig. 1 and Fig. 3. Here it must be mentioned that, due to the broadening of the instruments and the slight gradients in density and temperature, no perfect separated plasmon pairs, characterizing different ionized target regions in the case of the simulation including impact ionization, can be obtained. Therefore, only one plasmon pair which is broadened to higher energy shifts can be observed.

Moreover, in the case without impact ionization, a temporal evolution of the plasma within the delay time from 100 fs to 350 fs can be obtained from the effective electron temperature and density and implies a decreasing electron temperature and an almost constant ionization degree with increasing delay times. This characterizes the deceleration of the electrons by the electrical fields of the ions where, although no impact ionization is considered, further field ionization processes may occur.

Table 1. Effective electron temperature and density determined from the Thomson scattering spectra of Fig. 5.

	Δt [fs]	ΔE [eV]	T_e [eV]	n_e [cm ⁻³]
with impact	100	10.95	4.5	$8.2 \cdot 10^{22}$
ionization	100	20.54	5.5	$3.0 \cdot 10^{23}$
without impact	100	15.75	9.2	$1.7 \cdot 10^{23}$
ionization	350	15.75	16.6	$1.6 \cdot 10^{23}$

6. Proposed experimental setup

The predicted experiment can be performed in a vacuum chamber directly connected to one of the beam lines BL 1-3 at FLASH, because for soft x-rays the entire FEL beam path, including the experiment, needs to be at a pressure below 10^{-6} mbar.

As sketched in Fig. 6, the plasma will be generated by the Titanium:Sapphire pump-probe laser system available at the FLASH I experimental hall [44] with laser parameters comparable to the parameters used for the calculations in Sec. 4. A typical laser pulse with a central wavelength of $\lambda = 800$ nm has a pulse length of 60 fs and contains 15 mJ of energy. We use an off-axis parabolic mirror to tightly focus the beam to a $8 \mu\text{m}$ FWHM focal spot, containing > 10 mJ of energy. The carbon foil will hence be irradiated at a maximum intensity of $2 - 3 \times 10^{16} \text{ W/cm}^2$, sufficient to generate hot electrons that impact-ionize the matter, as discussed in Sec. 4.

Figure 6. (color online) Proposed experimental setup for the measurement of impact ionization in carbon foils.

The laser amplified spontaneous emission contrast will be optimized and the number and amplitude of prepulses minimized so that no pronounced preplasma is created and the thin foil is still at solid density when the main pulse arrives.

For probing the plasma, the FEL beam with a central wavelength of 5 nm, typically $> 100 \mu\text{J}$ pulse energy and of order 100 fs pulse length is focused by a grazing-incidence, carbon-coated ellipsoidal beamline mirror onto the target. Shortly before the interaction region, the XUV beam passes through a small hole in the parabolic mirror. It has a beam waist diameter of $20 \mu\text{m}$ on the target.

Important for the success of the experiment is a decent control of the spatial and

temporal overlap between the optical pump and the XUV probe pulses. The FLASH pump-probe laser is synchronized to the FEL photo-cathode laser, but a temporal jitter of several 10 fs is unavoidable due to the spontaneous nature of the SASE lasing process. While the coarse temporal overlap at the target > 1 ps can be achieved by observing the scattered light by a fast photo diode and a GHz oscilloscope, shot-to-shot fs-precise measurements of the delay between the two laser pulses will be performed using the time-tool developed by Harmand *et al.* [45, 46].

In order to allow observation at a scattering angle of 90° , the carbon foil will be mounted at about 45° with respect to the incident beams. At 90° , the HiTRaX XUV spectrometer [47] will be installed which can be equipped with a 1800 lines/mm grating to cover the anticipated spectral range. It features a toroidal mirror which images the plasma 1:1 (in the zero order of the grating) onto the CCD with high spatial resolution of about $13 \mu\text{m}$. This can be used to ensure spatial overlap of the optical and the XUV foci. Also, since the optical laser focus is about $2\times$ smaller than the probing XUV focus, the spectrometer can distinguish between the central heated region and cold scattering from the boundaries. At 160° scattering angle, a flat-field grating [48] with a line density of 2400 mm^{-1} can be employed. Predicted by the calculations shown in Fig. 5 and Tab. 1, the applied spectrometers need to be capable of detecting the plasmon signal level at ± 15 eV from the elastic peak ($\Delta E/E = 6\%$ or $\Delta\lambda = 0.3 \text{ nm}$ at $\lambda = 5 \text{ nm}$) with high dynamic range. Therefore, the spectrometers need high dispersion and sufficient spectral resolution, while FLASH needs to be tuned to a narrow bandwidth.

The efficiency of these spectrometers is of order $N_{\text{detected}}/N_{\text{incident}} \sim 10^{-5}$ to 10^{-6} . Thus, on the basis of Fig. 5, we expect in a single shot for 10^{12} incoming photons to detect of order ≈ 100 elastically and ≈ 10 inelastically scattered photons at an angle of 160° in a single exposure. Accumulation of several exposures will be a likely mode of operation. Both the optical and the XUV laser can operate up to 10 Hz. However, the repetition rate of the experiment is limited by the target translation and the spectrometer CCD camera readout rate. When binning or recording only a region of interest of the CCD chip, up to 2 Hz repetition rate could be achieved.

As additional diagnostics, the XUV spectrometers simultaneously observe the $K\alpha$ fluorescence at 4.4 nm from the pumped region, which corresponds to an energy shift of $\Delta E \approx 35$ eV from the elastic feature of Fig. 5 allowing the measurement of the plasmons with a shift of up to 25 eV (see Tab. 1). The XUV probe photon energy is below the K-edge of carbon and hence cannot produce K-vacancies. When blue-shifted satellites of $K\alpha$ emerge, the ion abundance of the laser-generated plasma could be deduced from the emission spectrum.

7. Conclusions

We have simulated the interaction between an intense optical short-pulse laser with a thin carbon foil with the PIC code VLPL3D. We have compared simulations with and without additional impact ionization and found that the consideration of impact

ionization in the laser-matter interaction is important. This effect was studied dependent on the pump laser intensity; it was found to be essential for laser intensities exceeding $I = 10^{16}$ W/cm². For instance, for $I > 10^{17}$ W/cm² we have obtained a much higher ionized foil with lower electron temperatures considering impact ionization. Furthermore, also the interior of the foil is highly ionized due to impact ionization. The temporal evolution of the carbon foil indicates a constant ionization degree and decreasing electron temperatures.

We were able to calculate the overall Thomson scattering signal for $I > 10^{17}$ W/cm² from the simulated electron temperature and density profiles gained from the PIC simulations within the Born-Mermin Approximation. Although the scattering signal shows only slight differences between the simulations with and without impact ionizations, a proper resolution of the plasmon peaks via Thomson scattering would reveal the electron temperature which is a direct measure of the influence of impact ionization processes, see Fig. 5 and Tab. 1. Therefore, the proposed pump-Thomson scattering probe experiment at FLASH would be an important step towards a better understanding of the complex electron kinetics in intense laser fields on ultra-short time scales. Furthermore, these results would allow more accurate predictions for the plasma parameters in similar experiments.

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References

- [1] B. A. Remington, R. M. Cavallo, M. J. Edwards, D. D.-M. Ho, B. F. Lasinski, K. T. Lorenz, H. E. Lorenzana, J. M. McNaney, S. M. Pollaine, and R. F. Smith, *Astrophys. Space Sci.* **298**, 235 (2005)
- [2] J. J. Fortney, S. H. Glenzer, M. Koenig, B. Militzer, D. Saumon, and D. Valencia, *Phys. Plasmas* **16**, 041003 (2009)
- [3] R. P. Drake, *Phys. Plasmas* **16**, 055501 (2009)
- [4] E. I. Moses, R. N. Boyd, B. A. Remington, C. J. Keane, and R. Al-Ayat, *Phys. Plasmas* **16**, 041006 (2009)
- [5] C. on High Energy Density Plasma Physics, P. S. Committee, and N. R. Coun-

- cil, Frontiers in High Energy Density Physics: The X-Games of Contemporary Science (National Academies Press, 2003)
- [6] V. S. Popov, Phys. Usp. **47**, 855 (2004)
- [7] C. E. Max, J. Arons, and A. B. Langdon, Phys. Rev. Lett. **33**, 209 (1974)
- [8] F. Brunel, Phys. Rev. Lett. **59**, 52 (1987)
- [9] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979)
- [10] W. L. Kruer and K. Estabrook, Phys. Fluids **28**, 430 (1985)
- [11] A. Pukhov, Rep. Progr. Phys. **66**, 47 (2003)
- [12] P. Gibbon, Short Pulse Laser Interactions with Matter: An Introduction (World Scientific Publishing Company, London, 2005)
- [13] P. Mulser and D. Bauer, High power laser-matter interaction (Springer, 2010)
- [14] R. Fäustlin, T. Bornath, T. Döppner, S. Düsterer, E. Förster, C. Fortmann, S. H. Glenzer, S. Göde, G. Gregori, R. Irsig, T. Laarmann, H. Lee, B. Li, K.-H. Meiwes-Broer, J. Mithen, B. Nagler, A. Przystawik, H. Redlin, R. Redmer, H. Reinholz, G. Röpke, F. Tavella, R. Thiele, J. Tiggesbäumker, S. Toleikis, I. Uschmann, S. Vinko, T. Whitcher, U. Zastra, B. Ziaja, and T. Tschentscher, Phys. Rev. Lett. **104**, 125002 (2010)
- [15] T. Bornath, P. Hilse, and M. Schlanges, Laser Phys. **17**, 591 (2007)
- [16] T. Fennel, L. Ramunno, and T. Brabec, Phys. Rev. Lett. **99**, 233401 (2007)
- [17] S. H. Glenzer, G. Gregori, R. W. Lee, F. J. Rogers, S. W. Pollaine, and O. L. Landen, Phys. Rev. Lett. **90**, 175002 (2003)
- [18] S. H. Glenzer, O. L. Landen, P. Neumayer, R. W. Lee, K. Widmann, S. W. Pollaine, R. J. Wallace, G. Gregori, A. Höll, T. Bornath, R. Thiele, V. Schwarz, W.-D. Kraeft, and R. Redmer, Phys. Rev. Lett. **98**, 065002 (2007)
- [19] A. L. Kritcher, P. Neumayer, J. Castor, T. Döppner, R. W. Falcone, O. L. Landen, H. J. Lee, R. W. Lee, E. C. Morse, A. Ng, S. Pollaine, D. Price, and S. H. Glenzer, Science **322**, 69 (2008)
- [20] U. Zastra, P. Sperling, M. Harmand, A. Becker, T. Bornath, R. Bredow, S. Dziarzhytski, T. Fennel, L. Fletcher, E. Förster, S. Göde, G. Gregori, V. Hilbert, D. Hochhaus, B. Holst, T. Laarmann, H. J. Lee, T. Ma, J. P. Mithen, R. Mitzner, C. Murphy, M. Nakatsutsumi, P. Neumayer, A. Przystawik, S. Roling, M. Schulz, B. Siemer, S. Skruszewicz, R. Thiele, J. Tiggesbäumker, S. Toleikis, T. Tschentscher, T. White, M. Wöstmann, H. Zacharias, T. Döppner, S. H. Glenzer, and R. Redmer, Phys. Rev. Lett. **112**, 105002 (2014)
- [21] S. H. Glenzer and R. Redmer, Rev. Mod. Phys. **81**, 1625 (2009)
- [22] R. Thiele, T. Bornath, C. Fortmann, A. Höll, R. Redmer, H. Reinholz, G. Röpke, A. Wierling, S. H. Glenzer, and G. Gregori, Phys. Rev. E **78**, 026411 (2008)
- [23] A. Höll, T. Bornath, L. Cao, T. Döppner, S. Düsterer, E. Förster, C. Fortmann, S. H. Glenzer, G. Gregori, T. Laarmann, K.-H. Meiwes-Broer, A. Przystawik, P. Radcliffe, R. Redmer, H. Reinholz, G. Röpke, R. Thiele, J. Tiggesbäumker, J. Toleikis, N. X. Truong, T. Tschentscher, I. Uschmann, and U. Zastra, High Energy Dens. Phys. **3**, 120 (2007)
- [24] C. Fortmann, R. Thiele, R. Fäustlin, T. Bornath, B. Holst, W.-D. Kraeft, V. Schwarz, S. Toleikis, T. Tschentscher, and R. Redmer, High Energy Dens. Phys. **5**, 208 (2009)
- [25] R. Thiele, P. Sperling, M. Chen, T. Bornath, R. R. Fäustlin, C. Fortmann, S. H. Glenzer, W.-D. Kraeft, A. Pukhov, S. Toleikis, T. Tschentscher, and R. Redmer, Phys. Rev. E **82**, 056404 (2010)
- [26] P. Sperling, T. Liseykina, D. Bauer, and R. Redmer, New J. Phys. **15**, 025041 (2013)
- [27] A. Pukhov, J. Plasma Phys. **61**, 425 (1999)
- [28] W. Lotz, Z. Phys. **206**, 205 (1967)
- [29] W. Lotz, Z. Phys. **216**, 241 (1968)
- [30] A. Karmakar and A. Pukhov, Laser Part. Beams **25**, 371 (2007)
- [31] E. d’Humieres, Y. Sentoku, and A. Kemp, J. Phys.: Conf. Series **112**, 022108 (2008)
- [32] C. Jacoboni and L. Reggiani, Rev. Mod. Phys. **55**, 645 (1983)
- [33] O. Ciricosta, S. M. Vinko, H.-K. Chung, B.-I. Cho, C. R. D. Brown, T. Burian, J. Chalupsky, K. Engelhorn, R. W. Falcone, C. Graves, V. Hajkova, A. Higginbotham, L. Juha, J. Krzywinski,

- H. J. Lee, M. Messerschmidt, C. D. Murphy, Y. Ping, D. S. Rackstraw, A. Scherz, W. Schlotter, S. Toleikis, J. J. Turner, L. Vysin, T. Wang, B. Wu, U. Zastra, D. Zhu, R. W. Lee, P. Heimann, B. Nagler, and J. S. Wark, *Phys. Rev. Lett.* **109**, 065002 (2012)
- [34] D. J. Hoarty, P. Allan, S. F. James, C. R. D. Brown, L. M. R. Hobbs, M. P. Hill, J. W. O. Harris, J. Morton, M. G. Brookes, R. Shepherd, J. Dunn, H. Chen, E. Von Marley, P. Beiersdorfer, H. K. Chung, R. W. Lee, G. Brown, and J. Emig, *Phys. Rev. Lett.* **110**, 265003 (2013)
- [35] H. A. Baldis, J. Dunn, M. E. Foord, and W. Rozmus, *Rev. Sci. Instrum.* **73**, 4223 (2002)
- [36] J. Chihara, *J. Phys. F* **17**, 295 (1987)
- [37] J. Chihara, *J. Phys. Cond. Matter* **12**, 231 (2000)
- [38] H. Reinholz, R. Redmer, G. Röpke, and A. Wierling, *Phys. Rev. E* **62**, 5648 (2000)
- [39] A. Selchow, G. Röpke, and A. Wierling, *Contrib. Plasma Phys.* **42**, 43 (2002)
- [40] P. Sperling, R. Thiele, B. Holst, C. Fortmann, S. Glenzer, S. Toleikis, T. Tschentscher, and R. Redmer, *High Energy Dens. Phys.* **7**, 145 (2011)
- [41] G. Gregori, S. H. Glenzer, F. J. Rogers, S. M. Pollaine, O. L. Landen, C. Blancard, G. Faussurier, P. Renaudin, S. Kuhlbrodt, and R. Redmer, *Phys. Plasmas* **11**, 2754 (2004)
- [42] J. J. MacFarlane, I. E. Golovkin, and P. R. Woodruff, *J. Quant. Spectrosc. Radiat. Transfer* **99**, 381 (2006)
- [43] D. A. Chapman and D. O. Gericke, *Phys. Rev. Lett* **107**, 165004 (2011)
- [44] S. Toleikis, R. Fäustlin, L. Cao, T. Döppner, S. Düsterer, E. Förster, C. Fortmann, S. Glenzer, S. Göde, G. Gregori, R. Irsig, T. Laarmann, H. Lee, B. Li, J. Mithen, K.-H. Meiwes-Broer, A. Przystawik, P. Radcliffe, R. Redmer, F. Tavella, R. Thiele, J. Tiggesbäumker, N. Truong, I. Uschmann, U. Zastra, and T. Tschentscher, *High Energy Dens. Phys.* **6**, 15 (2010), ISSN 1574-1818
- [45] M. Harmand, C. Murphy, C. R. D. Brown, M. Cammarata, T. Döppner, S. Düsterer, D. Fritz, E. Förster, E. Galtier, J. Gaudin, S. H. Glenzer, S. Göde, G. Gregori, V. Hilbert, D. Hochhaus, T. Laarmann, H. J. Lee, H. Lemke, K.-H. Meiwes-Broer, A. Moinard, P. Neumayer, A. Przystawik, H. Redlin, M. Schulz, S. Skruszewicz, F. Tavella, T. Tschentscher, T. White, U. Zastra, and S. Toleikis, *J. Instr.* **7**, 08007 (2012)
- [46] M. Harmand, R. Coffee, M. R. Bionta, M. Chollet, D. French, D. Zhu, D. Fritz, H. Lemke, N. Medvedev, B. Ziaja, S. Toleikis, and M. Cammarata, *Nat. Photon.* **7**, 215 (2013)
- [47] R. R. Fäustlin, U. Zastra, S. Toleikis, I. Uschmann, E. Förster, and T. Tschentscher, *J. Instr.* **5**, P02004 (2010)
- [48] U. Zastra, V. Hilbert, C. R. D. Brown, T. Döppner, S. Dziarzhytski, E. Förster, S. H. Glenzer, S. Göde, G. Gregori, M. Harmand, D. Hochhaus, T. Laarmann, H. J. Lee, K.-H. Meiwes-Broer, P. Neumayer, A. Przystawik, P. Radcliffe, M. Schulz, S. Skruszewicz, F. Tavella, J. Tiggesbäumker, S. Toleikis, and T. White, *J. Instr.* **6**, 10001 (2011)