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Abstract. The short pulse duration and high intensity of the FLASH (Free-electron LASer in Hamburg) allows us to generate and probe homogeneous warm dense non-equilibrium hydrogen within a single extreme ultraviolet (EUV) light pulse [1]. By analyzing the spectrum of the 13.5 *nm* Thomson scattered light we determine the plasma temperature and density. We find that classical models of this interaction are in good agreement with our dense plasma conditions. In a FEL-pump FEL-probe experiment droplets of liquid hydrogen and their scattering behaviour for different pump-probe setups were observed under 20° and 90°. We find that the scattering behaviour of the scattered intensity depends on the scattering angle.

Keywords: FEL, Dense Plasma, XUV Spectroscopy, Hydrogen, Warm Dense Matter
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INTRODUCTION

The investigation of warm dense matter has become of great interest for current fields of research [2]. The intermediate state between condensed matter and ideal plasma exhibits both moderate free electron temperature ($T_e \sim 10^0 \dots 10^2\ eV$) and high free-electron densities ($n_e \sim 10^{21} \dots 10^{26}\ cm^{-3}$). Such states can be observed in cores of large planets (i.e. Jupiter), in solid to plasma transitions and in x-ray driven inertial fusion experiments. To understand processes of warm dense matter the equation of states and the time dependent-evolution have to be known. In our experiments we were able to access plasma parameters and observe a distinct delay dependence in FEL pump - FEL probe setups for scattering under 90° which corresponds to a temporal evolution of the state.

SELF-THOMSON SCATTERING

To determine fundamental plasma parameters the following setup is used. A FEL beam passes horizontally through a target chamber such, that the focus with $\sim 20-30\ \mu m$ (FWHM) is located in the center of the chamber [4]. The photon energy is adjusted to $92\ eV$, corresponding to a photon wavelength of 13.5 nm with a bandwidth of $\sim 1.0\%$, and a pulse energy of up to 100 μJ at a pulse duration of $15-50\ fs$ [5]. At the focus a hydrogen pellet source injects liquid hydrogen droplets at a temperature of 20 K with a filament diameter of $25-30\ \mu m$ and an atom density of $n = 4.2 \times 10^{22} cm^{-3}$. Further a soft x-ray spectrometer is mounted vertically at a scattering angle of 90°[6]. In the so called self-Thomson scattering configuration pumping and probing of the sample happens within the same pulse. The interaction of the leading edge of the soft x-ray FEL with the cold sample creates a plasma. Simultaneously scattering occurs from the transiently changing droplet during the pulse. Photons will be scattered at collective electron waves, the plasmons. Figure 1 shows a spectrum for 15 min integration time, which compares to an averaging over 4500 FEL pulses at an average intensity of 15 μJ. The spectrum shows equally red and blue shifted peaks from electronic plasma which indicate the effect of plasmons. Comparing with simulations for different models of impact ionization this observation indicates that a free-electron plasma with electron equilibration was generated. Within the pulse duration of 40 fs impact ionization is the main interaction during the evolution of the plasma [7]. In a quantitative analysis of the spectra the photon energy shift of the plasmons with respect to the incident radiation is compared. We obtain a density of $n_e = (2.8 \pm 0.2) \times 10^{20}\ cm^{-3}$ corresponding to $\sim 1\%$ ionization in the sample. The free-electron temperature is determined through the intensity ratio of the two plasmon peaks via detailed balance [3] and a value of $T_e = 13 \pm 3.25\ eV$ is found. The measurement is in good agreement with a model based

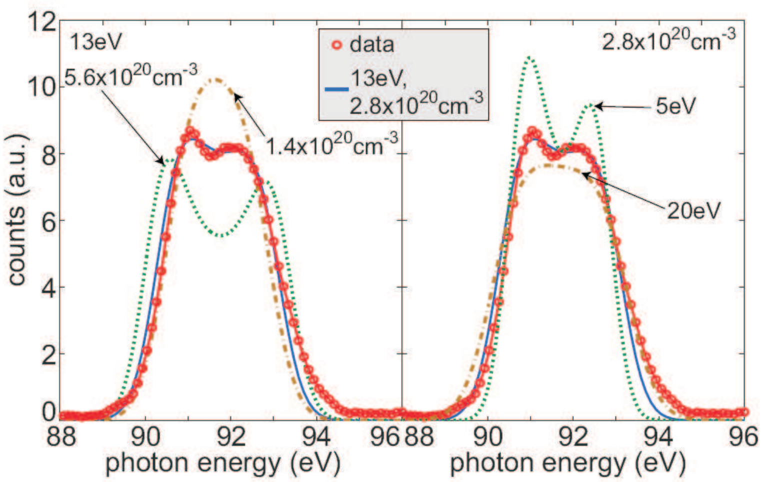

FIGURE 1. Determination of plasma parameters. **Left:** For a fixed free-electron temperature of $T_e = 13\ eV$ the free-electron density n_e is altered to fit the measurement data. **Right:** For a fixed free-electron density of $n_e = 2.8 \times 10^{20} cm^{-3}$ the free electron temperature is altered to fit the measurement data. Best fit is found for parameters $T_e = 13\ eV$, $n_e = 2.8 \times 10^{20} cm^{-3}$ [3].

on classical electron-electron collisions [8].

FEL - PUMP FEL - PROBE SCATTERING

In another experiment pump-probe effects dependent on the delay were object of inquiry. To adjust for different pump-probe delays a beamsplitter as described in [9] is used to create a pump and a probe pulse from the same FEL pulse. Therefore a mirror is moved into the beam to split the beam profile into two equal parts. Each beam now passes an autocorrelator arm with multiple mirrors. Moving the mirrors corresponds to a variation of the length of one of the beam paths. In this way different pump-probe delays can be adjusted. Moving the split and delay line into the beam path leads to an additional loss of FEL pulse energy of $\sim 50\%$ due to reflection losses at the introduced mirrors [9]. The positioning stage of the mirrors allows for a movement which corresponds to delays between $-1 < 0 < 5$ *ps*. To probe only the heated region of the hydrogen, the two beams have to overlap. Mirrors inside the variable arm can be tilted to achieve the spatial overlap of the two beams. For each delay the overlap has to be readjusted.

In addition to former experiments in this case a second spectrometer measuring under a scattering angle of 20° in forward direction is attached to the stationary vacuum chamber setup. Measured spectra are now integrated over the whole wavelength range of the signal. Figure 2 displays the normalized scattered intensity over the pump-probe delay for each scattering angle. The scattering signal under 90° observation angle clearly reveals a delay dependence. While for zero-delay the described self-Thomson scattering takes place, we find that scattered intensity increases within 1 *ps* and then slowly decays over a period of several *ps*. The asymmetric shape of the graph around 0 *ps* is caused by the non-ideal split of the beam. Evaluating the scattered intensity under 20° such obvious delay dependent behaviour cannot be found. A field of current research is to explain this angle and delay dependent effect and find an appropriate model to reproduce the results. One possible explanation for this effect is that the 90° scattering signal is dominated

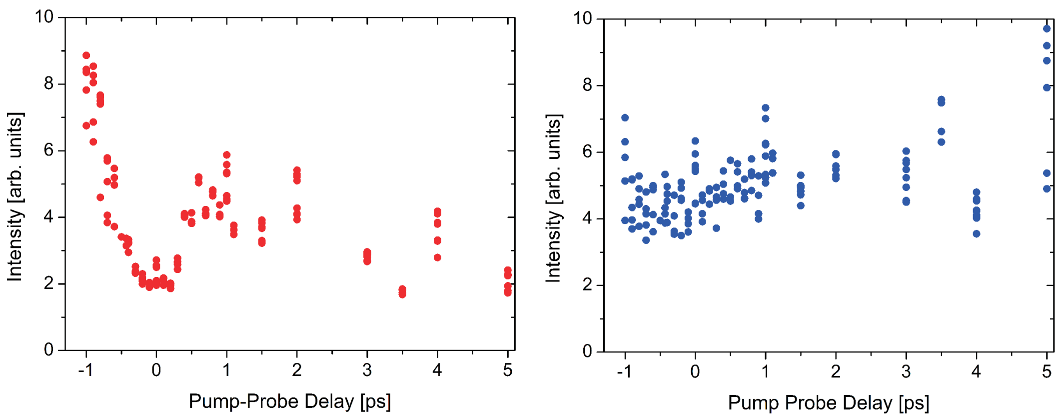

FIGURE 2. Normalized integrated scattered intensity. **Left:** Delay dependent scattering signal under 90° scattering angle. **Right:** Delay dependent scattering signal under 20° scattering angle.

by a thin heated front layer, whereas in forward direction we mainly observe how the remaining part of the droplet is heated and thus leading to different behaviour.

SUMMARY AND CLOSING REMARKS

An ultrashort XUV FEL pulse was used to create and probe a plasma from liquid hydrogen droplets. The fundamental plasma parameters (T_e, n_e) for Self-Thomson-scattering can be determined from the scattered spectrum. In the pump-probe case, the scattered intensity reveals a distinct delay dependency for a scattering angle of 90°. A delay effect for the intensity scattered in forward direction under 20°, if at all present, is very weak. Future plans comprise the observation of the delay dependent effect under more angles. A theoretical model to explain the angular and delay dependent behaviour is yet under construction. Ideas point in the direction of a non-homogeneously heated target.

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