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Soft x-ray scattering using FEL radiation for probing near-solid density plasmas at few electronvolt temperatures

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Abstract

We report on soft x-ray scattering experiments on cryogenic hydrogen and simple metal targets. As a source of intense and ultrashort soft x-ray pulses we have used free-electron laser radiation at 92 eV photon energy from FLASH at DESY, Hamburg. X-ray pulses with energies up to 100 μJ and durations below 50 fs provide interaction with the target leading simultaneously to plasma formation and scattering. Experiments exploiting both of these interactions have been carried out, using the same experimental setup. Firstly, recording of soft x-ray inelastic scattering from near-solid density hydrogen plasmas at few electronvolt temperatures confirms the feasibility of this diagnostics technique. Secondly, the soft x-ray excitation of few electronvolt solid-density plasmas in simple metals could be studied by recording soft x-ray line and continuum emission integrated over emission times from fs to ns.

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Keywords: free-electron laser, soft x-ray spectroscopy, inelastic x-ray scattering, strongly-coupled plasmas, ultrafast processes, pump-probe experiments

1. Introduction

Short-wavelength radiation exhibits significant differences in its interaction with matter compared to near-visible radiation. This had led to the proposal to employ intense, ultrafast, tunable and bright x-ray sources in studying properties of dense plasmas at an un-paralleled level of detail [1]. Several studies suggested to create solid density plasmas by intense femtosecond x-ray pulses [Fajardo, MtV-TDR] or to probe dense plasmas using various x-ray scattering and spectroscopy techniques [Riley, Gle0, Rozmus, Höll-HEDP]. Since existing conventional sources could not provide x-ray radiation with the required properties these experiments were until recently not possible. The first facility to provide intense, femtosecond, high-brightness, soft x-ray radiation is the free-electron laser (FEL) facility FLASH at DESY, Hamburg starting user operation in 2005 [FEL1, FEL2]. In this paper we report on two types of soft x-ray plasma physics experiments, both carried out for their first time and using 92 eV FEL radiation. Both experiments aim at the investigation of thermo-dynamical properties such as electron temperature, electron density and ionization for strongly coupled plasma systems. In particular the regime of near solid electron densities of $n_e = 10^{21} - 10^{23} cm^{-3}$ and temperatures of few up to tens of electronvolts is targeted.

In contrast to ideal plasmas for strongly-coupled plasmas correlations between the charged particles have to be considered. The regime of strongly-coupled plasmas can be identified by the ratio of Coulomb energy over thermal energy, i.e. the dimensionless coupling parameter $\Gamma = e^2 / (4\pi\varepsilon_o \bar{d} k_B T_e)$ being larger than unity and $\bar{d} = \left(4/3\,\pi\, n_e\right)^{-1/3}$. The interest in studying these systems experimentally arises from the complexity of the theoretical description and the necessity to verify the applicability of models using experimental data. Experiments have been limited so far by the fact that near-visible laser methods have intrinsic difficulties with the investigation of near-solid density matter. Using near-visible radiation the probing of dense matter is not possible due to strong absorption while the generation of plasmas using high intensities is always accompanied by complex shock wave creation. X-rays overcome both problems due to their largely increased penetration power.

2. Description of experimental techniques

2.1. Measuring near-solid density plasma parameters using inelastic soft x-ray scattering

The measurement of plasma parameters such as temperature, free electron density or ionization is required for the investigation of equation-of-state properties. One standard technique is Thomson scattering using near-visible radiation [vts]. The applicability of this method is limited to plasmas with much smaller densities than targeted here. For near-solid density plasmas x-ray radiation is required and the technique of x-ray Thomson scattering had been successfully introduced using high energy laser sources and few keV x-rays [Glenzer1, Glenzer2]. Since FEL pulses provide similar photon numbers per pulse as used in the reported high energy laser experiments, and simultaneously an even higher brightness it is straightforward to implement this inelastic x-ray scattering technique using these new sources. Much higher repetition rates facilitate in addition the investigation of various targets and target configuration as well as scanning wide parameter ranges. At the same time the high time-resolution in FEL experiments enables to investigate the dynamics of plasma formation and equilibration. We report here initial experiments carried out in the soft x-ray regime at 92 eV photon energy. The scattering kinematics in inelastic x-ray scattering is determined by the momenta of incoming x-ray photon $\vec{k}_i$ and scattered photon $\vec{k}_f$, where the momentum $\vec{K} = \vec{k}_i - \vec{k}_f$, $|\vec{K}| = K$ is transferred to the scattering particle. This kinematics determines if the collective plasmon-like character of electronic excitations or non-collective single electron properties are probed. To distinguish the two regimes the scattering parameter $\alpha = 1/(K\lambda_{D,sc})$ is used. $\alpha > 1$ corresponds to the collective regime where the probed length scales are larger than the Debye screening length $\lambda_{D,sc}^2 = \varepsilon_o k_B T/(n_e e^2)$. Here, scattering from collective electronic excitations, so-called plasmons, can be observed. In the non-collective regime, $\alpha < 1$, the probed length scale is shorter than $\lambda_{D,sc}$ and the momentum of individual electrons is probed. The energy transfer from the photon to the single electron is $\hbar\varpi = \hbar(\varpi_i - \varpi_f)$. For bound electrons with $\hbar\varpi \geq E_B$, and the binding energy E_B of this electron, Compton scattering becomes observable. Since the energy transfer in the soft x-ray regime is very small, typically below the energy resolution and difficult to investigate, these first inelastic x-ray scattering experiments using FEL sources have been carried out in the collective scattering mode. In the collective mode scattering from the plasmon gives rise to down- and up-shifted resonances, relative to the elastic scattering. From the energy difference the electron density can be estimated and the peak height relation allows an independent estimation of the electron temperature [Hoe07]. Experimentally, a near-visible femtosecond laser is used to heat a liquid hydrogen target with an initial density below solid-density. We estimate that the plasma equilibrates within a few picoseconds and before the soft x-ray scattering measurement of plasma parameters occurs. Using two spectrometers at different scattering angles θ the simultaneous measurement of the amount of elastic scattering for two values of α, respectively K provides a possibility to investigate scattering from electrons bound to the ions [GRE].

2.2. Creation of solid-density plasmas using soft x-ray radiation

The current operation of FLASH allows obtaining intensities up to 10^{17} Wcm^{-2} by focusing the soft x-ray FEL beam. The interaction of the focused soft x-ray radiation with solid-density matter can lead in a small volume to an energy deposition of up to $\sim 10^3$ kJ/cm^3 and subsequent plasma formation. The energy absorption occurs during the duration of the FEL pulse of few ten femtoseconds during which the material cannot expand. For our experimental conditions and sample materials the primary absorption process is photoabsorption by L-shell electrons. Initially, the material enters into a highly excited, non-equilibrium state that develops with time after the FEL impact. During the entire cycle the sample transits from strongly-correlated cold matter, to a highly excited non-equilibrium plasma, to an equilibrated plasma state and finally cools down while expanding. Both continuum and line emission occur at different times in this cycle. The spectral shape of the continuum radiation and the relative intensities of plasma emission lines can be used to determine plasma parameters [Zas08]. In experiments one has to consider averaging effects due to spatially varying energy deposition and to time integration of the developing plasma states. In these initial experiments no time resolution could be applied to the spectral measurements therefore it is not possible to determine when radiation from the various emission channels occurred.

3. Experimental setup

Experiments have been carried out using soft x-ray radiation provided by FLASH, an FEL facility operating in the self-amplified spontaneous emission (SASE) mode [Sal]. In FLASH very low emittance electron bunches are generated in a low-emittance injector and are immediately accelerated to avoid space charge effects. After two compression steps using magnetic chicanes the electrons are accelerated to their final energy of 300 to 1000 MeV, producing soft x-ray FEL radiation in the fixed gap 30 m long permanent magnet undulator in the range 30 to 200 eV [Tie09]. 92 eV corresponds to an electron energy of 700 MeV. In the employed operation mode of FLASH the electron bunch has a high intensity head generating x-ray pulse durations of 15 – 50 fs with a bandwidth smaller 1.0 % and pulse energies up to 150 μJ. These x-ray pulses are transported to the experiments using carbon-coated mirrors operated at a grazing angle of 2 and 3 deg. The experiments have been carried out at BL2 of FLASH with two flat and one ellipsoidal mirrors, the later producing a focal spot of 20 – 30 μm diameter (FWHM). The total beamline transmission is considered to be 64 ± 4 % [Tie09].

For the experiments reported here fluctuations of the pulse energy and of the spectral distribution need to be considered. The pulse energy I_o is measured pulse-by-pulse and this measurement is used for normalization of single-shot data [Tie08]. For measurements integrating over several x-ray pulses the averaged pulse energy is used for normalization. The spectral distribution fluctuates also from shot-to-shot as is shown in Fig. 1. In this case of particular unstable operation of the FEL the averaged distribution exhibits a bandwidth of ~2% corresponding to 2 eV, and the single spectra indicate a mode structure with a typical peak width of 0.3–0.5 eV. Since only few modes are populated the weight of the spectral distribution can vary strongly from shot-to-shot. In order to normalize the scattering spectra with respect to this fluctuation an additional spectrometer measures the spectral distribution of the incident beam. Fluctuations of the temporal distribution of the FEL pulses occur similar to the spectral distribution, but are not considered important in these experiments. FLASH can accelerate trains of 1-800 electron bunches with a repetition rate of 5 Hz. The repetition rate of bunches within the train can be selected between 40 kHz and 1 MHz. Most of the experiments reported here have used single pulses or single pulses at 5 Hz repetition rate. In a few cases trains with up to 30 pulses at 5 Hz corresponding to 150 pulses per second have been used to increase the counting statistics.

The experimental setup is mounted in ultrahigh vacuum conditions using a total of 2200 l/s pumping speed. The geometry is chosen such that the spectrometers are mounted in the vertical plane at scattering angles θ equal 0, 16 and 90 degree. The choice of the vertical plane follows from the very high degree of linear polarization of incident radiation in the horizontal plane. The spectrometer at $\theta = 0$ degree is used for measuring the spectral distribution of the incident radiation. In flat-field geometry a planar variable line spacing grating with 1200 lines/mm is mounted at ~170 cm from the interaction point. A 100 μm slit is used for background reduction and vacuum separation. For detection a back-illuminated CCD is used and we obtain an energy resolution $\Delta E/E \cong 3{,}6 \times 10^{-3}$ [Bei99]. The spectrometer at $\theta = 16$ degree employs the same spectrometer principle and the same grating, which is mounted with 23.5 cm much closer to the interaction point. The main spectrometer, mounted at $\theta = 90$ degrees, had undergone an optimization with respect to large solid angle, high throughput and high spectral resolution in order to maximize the signal level. For the first experiment a spectrometer based on a transmission grating was used [Jas83], but artifacts arising from the support grid of the grating and the need for improved alignment and higher efficiency have led to design and construction of a new spectrometer [Fäu09]. This spectrometer employs a toroidal mirror together with an 800 lines/mm variable line spacing grating, accepts a solid angle of $19\times10^{-4}\,sr$, obtained a resolution of $\Delta E/E \cong 5\times10^{-3}$ at 92 eV and has an estimated throughput of $\approx 4\times10^{-2}$ including detection efficiency by the back-illuminated CCD. In addition to the soft x-ray spectrometers we use optical spectrometers for detection of emission radiation in the near-visible regime. Analysis of line and continuum emission in this regime should provide further information about the temperature of the hydrogen plasma.

The targets are placed in the center of the main chamber. The inelastic scattering experiment uses a liquid hydrogen jet produced by 10 – 20 µm nozzles at a temperature around 20 K [Prys09]. The jet diameter under ideal conditions is equal to the nozzle of the liquid hydrogen source. The preparation of the liquid jet can lead to a variety of jet conditions. The phase space of liquid hydrogen is rather dense in this regime and small fluctuations of parameters like pressure or temperature and impurities will lead to rather strong variations. In particular, we have observed that the mean density of the liquid jet can vary strongly. In the ideal condition we observe a homogeneous jet of liquid hydrogen with a mass density $\rho = 0{,}0706\,g\,cm^{-3}$. In another operation mode the hydrogen is ejected in tiny droplets with liquid density forming a jet with a mean density approximately 5 – 10 times less than for the liquid. The solid samples are mounted on a manipulator enabling translation to the chamber center once the liquid hydrogen source is retracted. The incidence angle of FEL radiation is roughly 45 degree with respect to the surface normal.

The near-solid density hydrogen plasma is created using a femtosecond optical laser delivering 3 – 5 mJ pulses at 800 nm at 5 Hz into a focal spot of ~30 µm diameter. A nearly collinear excitation geometry using a parabolic mirror with a central hole is chosen. With a measured pulse duration of roughly 150 fs obtained by compression of the stretched pulse just before entering the vacuum chamber this system reaches intensities of $\geq 10^{15}$ Wcm^{-2} [Red09]. The laser is synchronized using a radiofrequency clock to the arrival of the x-ray pulse with an accuracy of few ps over a duration of several hrs [Rad07]. Sub-picosecond time resolution can be obtained in a pulse-by-pulse measurement of the temporal fluctuation of the optical laser with respect to the x-ray arrival [Azi09]. In the experiments reported here we use a time resolution of the order 1 – 2 ps obtained by cross-correlating the optical laser to visible synchrotron radiation using a streak camera [Rad07]. To improve the signal-to-noise ratio we always analyze differences of two measurements: One with the optical laser before the FEL, leading to plasma formation, and a second, with the optical laser after the FEL, thus probing the cold hydrogen system. In addition, background images without x-ray illumination and of similar duration are taken in order to account for stray scattering and detector noise.

In the reported experiments x-ray scattering emerges from an interaction volume formed by the crossing of the soft x-ray beam of 25 μm (FWHM) diameter and the cryogenic liquid hydrogen jet of cylindrical geometry and 20 μm diameter. The incident intensity in this scenario is $2{,}5\times10^{14}\,Wcm^{-2}$ corresponding to 30 μJ pulse energy at the target, 25 fs duration and 25 μm focal spot diameter. The absorption length of 92 eV radiation in liquid hydrogen of 9,5 μm [CXRO,Henke] enables that 12 % of the radiation is transmitted through the target. For the measurements from solids the FEL beam hits the surfaces under an angle close to 45 degrees and the absorption lengths are 0,036 μm and 0,039 μm for aluminum and magnesium, two of the samples which have been investigated respectively. These absorption lengths are valid for the unperturbed groundstate materials. If the deposited energy is sufficient to modify the material properties significantly, one has to consider a transiently changing absorption. We have simulated this effect using the HELIOS code [Mac06] assuming that the energy deposited by the FEL beam is absorbed through photo-absorption and inverse Bremsstrahlung. For the particular conditions the main mechanisms are bound-free (photoionisation) and free-free (inverse Bremsstrahlung) transitions. To determine the appropriate ratios the code uses the target charge state which is obtained from tabulated values via the current electron temperature which is obtained on a timescale much shorter than the pulse durations. The simulations confirm that the soft x-ray FEL pulse heats the target for more homogeneously than the optical laser pulse. We are currently investigating the effect of inhomogeneous heating of the liquid hydrogen jet by the optical laser leading to variations of the electron temperature and density. First analysis indicates that observation of plasma parameters from of the plasmon peak is relatively stable [Thi09].

For the experimental conditions of these experiments we obtain the following relation for the scattering parameter

$$\alpha = \frac{e\sqrt{n_e}}{K\sqrt{\varepsilon_o k_B T_e}} \cong 20.4 \times \frac{\sqrt{n_e\left[10^{22}\,cm^{-3}\right]}}{\sqrt{T_e\left[eV\right]}}, \qquad (1)$$

shown graphically in Fig. 2. One finds that in the case of liquid hydrogen scattering occurs in the collective regime for all densities between the liquid ($n_e = 4{,}2\times10^{22}\,cm^{-3}$) and expanded densities of below $n_e \approx 10^{20}\,cm^{-3}$ if one assumes that the electron temperatures do not exceed a few eV. For solids ($n_e \approx 10^{23}\,cm^{-3}$) temperatures can be considerably higher still fulfilling the condition for collective scattering. Using 95 µJ FEL pulses and scattering from a liquid hydrogen jet of ~20 µm diameter we are able to obtain significant scattering from a single shot (compare Fig 3). These are ideal conditions for this experiment since they allow measuring the beam properties of FEL beam on a shot-by-shot basis. Unfortunately we could not operate the whole experiment in this mode but had to collect scattering data from laser-heated hydrogen plasma using integration over several hundred shots. During integration both FEL pulse energy and mean density of the liquid jet were fluctuating. In this mode signal was collected over a predefined time and in parallel the mean FEL pulse energies and the spectral distribution were measured for normalization of the scattering data. In order to normalize the fluctuations of the liquid jet a monitoring signal is needed which is linear to the scattering probability of the FEL beam. We have tried two possibilities. First, one can use the transmitted beam intensity to determine the absorbed beam fraction. This method has shown to be not feasible since a detector for the transmitted beam gets overloaded with the optical pump laser beam. A second way is to use a fast, pulse resolved integral scattering signal. Both light scattering or particle emission have been analyzed in the multi-channel plate detector mounted for this purpose. The normalization using this signal seems to work in principle, but the error margin is very high.

Providing fresh target volumes is a prerequisite for integrating experiments. Using the liquid jet with an expansion speed ~60 m/s we calculate that fresh sample volumes are safely achieved for FEL repetition rates up 1 MHz. Using the femtosecond optical laser for pumping the system experiments are carried out using the 5 Hz repetition rate. In the solid experiments the target was continuously translated using the 5 Hz repetition rate of the FEL.

4. Results and discussion

The soft inelastic x-ray scattering experiments from liquid hydrogen can be separated into two parts. These are the experimental procedures to observe scattering of FEL radiation and detection using efficient spectrometers and the time-resolved investigation of the parameters of an optical laser prepared hydrogen plasma. The experiment can be subdivided into three groups: The scattering of FEL radiation includes the preparation and characterization of the FEL beam and the spectrometer for efficient detection. The target preparation and characterization includes as well the measurement of the target availability. And finally, the optical laser heating of the hydrogen plasmas.

For soft x-rays the absorption of the probing radiation by the target is considerable even in the case of the reduced density of liquid hydrogen. The energy absorbed from the focused FEL radiation will itself lead to strong excitation of the target eventually leading to plasma formation. The amount to which a transient change of the target affects the inelastic scattering, a process called self-scattering, is currently analyzed [Tol09]. The experimental results show that two parameters of FEL radiation are most critical to the success of these experiments. A pulse energy of order 30 – 50 μJ is needed to obtain a significant amount of scattered signal using single pulses or very short (few 10 seconds) integration times. On top of that, it is crucial that the liquid hydrogen source operates stably throughout the integration time in the high average density liquid jet mode. Short integration times can be still acceptable as the stabilization of parameters can work on this time scale. Extremely critical for the observation of plasmon peaks are the bandwidth of incident FEL radiation and the spectral resolution of the spectrometer. As shown in [Hoe07] the shift of the plasmon signal with respect to the elastic scattering is of the order few eV only. Smearing of the spectroscopic data by incident bandwidth or by spectrometer resolution therefore can wash out the experimental results. A total spectral resolution better than 1 % is therefore required for the conditions of these experiments. Figure 4 shows experimental data obtained from liquid hydrogen. Spectra are shown for the cases of optical laser arriving 3 ps before and 3 ps after the FEL pulse and integrating over 9000 pulses at 5 Hz. Since the two spectra do not differ significantly we subtract them after background subtraction and intensity normalization. The resulting difference signal seemingly gives a small signal. Also shown are the spectral compositions of the incident FEL radiation, measured at $\theta = 0$ deg and using the same integration times as for the scattered spectra. After normalization the difference profile of the incident FEL radiation shows similar features than the difference profile of scattered radiation. In this case it was likely that fluctuations of the spectral composition of FEL radiation over the integration period of the measurement are responsible for the difference profiles. This result demonstrates the crucial importance of a simultaneous measurement of the spectral composition of FEL radiation and the requirement to operate the FEL under very stable conditions in order to enable experiments of this kind. Comparing the peak width of the scattered radiation and the measured FEL spectrum we observe a clear broadening in the scattered spectrum. Whether this broadening is due to inelastic scattering near the elastic peak or is due to source broadening requires still further clarification. The oscillations of the signal away from the scattering peak is reproducible and is due to density modulations of the 200 nm Zr filter for visible light suppression inside the spectrometer.

Monitoring of the target availability is needed for establishing the absolute intensity of scattering or for the measurement of the dependence from the FEL pulse energy, e.g. to investigate the occurrence of self-scattering, but is in general not necessary. Fluctuations of the optical laser pulse energy and beam pointing need to be monitored in order to provide identical plasma conditions in these highly repetitive measurements. It was difficult to measure small possible beam drifts during the experiments reported here and we do not consider them in the further analysis. Nevertheless, the possibility introduced an experimental uncertainty.

These experiments are challenging in that the FEL, the liquid hydrogen jet, the optical laser, several spectrometers and diagnostics and the alignment of these elements have to operate at the same time and to full specification otherwise compromising the experimental outcome. Integration introduces uncertainty and broadening of experimental parameters which are crucial to the observation of results for the plasma parameters. Operation of FLASH at high pulse energies (>30 μJ) has shown the feasibility to carry out these measurements using single shot spectra. In this case the accumulation of a significant amount of spectral data with good resolution might be achieved by sorting data according to simultaneously measured FEL and optical laser data. Also, dependencies related to FEL intensity or target variation can be followed using this procedure.

The impact of the FEL pulse on solid targets was investigated by observation of emission radiation in the same experimental setup. The deposited energy leads to the formation of a plasma exhibiting emission characteristics that are rather different from those of a plasma created by an optical laser of similar intensity. Figure 5 shows a comparison of the emission spectra for aluminum following FEL and optical laser irradiation. Following soft x-ray excitation one observes, in addition to the elastically scattered soft x-ray radiation, a strong variation of line emission and continuum radiation indicating the different plasma state the aluminum has turned into after excitation. In contrast to the elastic and nearly elastic scattering the line and continuum emission can occur at delayed times after impact of the FEL pulse. The spectra shown in Fig. 6 integrate over timescales up to ns in which the plasmas may emit. The results for the characterization of FEL created warm dense Al plasmas using soft x-ray emission spectra have been published separately [Zas08]. In order to achieve high statistical accuracy during these measurements they are carried out integrating over a large number of FEL pulses. The variation of FEL pulse energy and the modification of target conditions related to the high repetition rate of the FEL pulses require further investigation using single shot spectra.

5. Conclusions

The experimental procedures for soft x-ray inelastic scattering experiments on cryogenic liquid hydrogen jets using FEL radiation have been developed. The observation of scattering spectra using efficient spectrometers is found to be possible. First results have been obtained for the time-resolved investigation of the parameters of an optical laser prepared hydrogen plasma. The interaction of the FEL pulse with the target leading to plasma heating, thereby changing the measured state, is still under investigation. The experiments reported here were the first of their kind carried out using FEL radiation. The results of these experiments indicate the requirements for future experimental campaigns with respect to diagnostics of FEL and optical laser radiation as well as sample availability. Scattering data has been collected in integrating 5 Hz mode for laser heated hydrogen plasmas varying the time delay between excitation and probing. These results are subject of a forthcoming publication. Most importantly we found that single shot scattering on liquid hydrogen gives significant scattering signal for a detailed study of plasma conditions. Applying single shot data collection offers the advantage to reduce statistical errors and will reduce the experimental uncertainty introduced by integration over varying parameters.

For solid aluminum targets the absorption of intense soft x-ray FEL radiation and subsequent formation of warm dense plasmas has been investigated by observation of the time-integrated emission spectrum which differs strongly from the spectrum after heating using optical lasers.

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Figure captions

Fig. 1 (colour only in web-version; b/w version available)

Single-shot spectra indicating the pulse-to-pulse fluctuation of the spectral distribution of incident SASE FEL pulses. The bold line corresponds to the spectral distribution averaged over 8 pulses and indicating the incident bandwidth of ~2 eV corresponding to ~2% relative bandwidth.

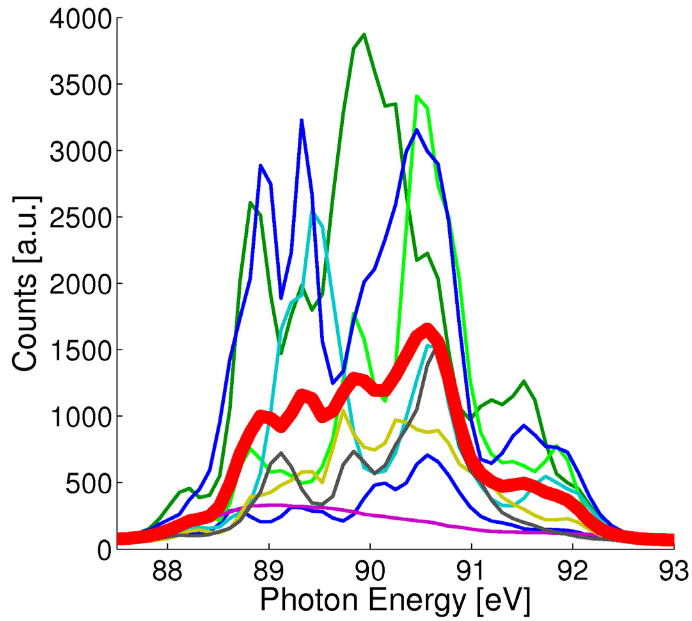

Fig. 2 (colour only in web-version; b/w version available)

Phase space representation for electron density n_e and temperature T_e, probing photon energy $\hbar\varpi = 92eV$ and scattering angle $\theta = 90\deg$. Lines for $\alpha = 0.5,1,2$ and $\Gamma = 1$ have been calculated according to the relations in the text and in equation (1). Grey areas indicate the expected parameter regimes for hydrogen and Al plasmas investigated. Densities of cold hydrogen and aluminum are indicated.

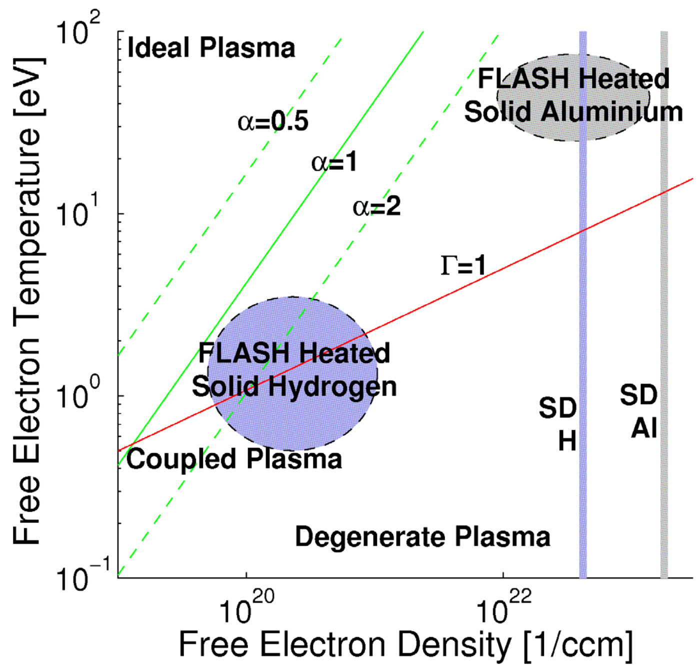

Fig. 3 (colour only in web-version; b/w version available)

Scattering signal from a single FEL pulse of 95 μJ energy obtained at the CCD of the HiTraX spectrometer [Fäu09] after background subtraction. 500 counts in the maximum correspond to a very high S/N ratio that is well beyond 50.

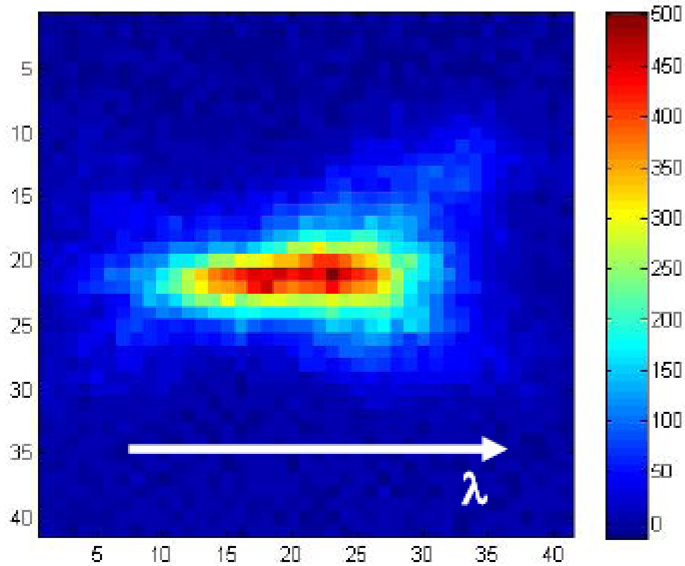

Fig. 4 (colour only in web-version; b/w version available)

Soft x-ray Thomson scattering spectra near 92 eV from hydrogen integrated over 9000 FEL pulses. Scattering spectra for the cases that the 800 nm optical laser hit the liquid hydrogen 3 ps prior and 3 ps after the FEL pulse and the corresponding FEL spectra are shown. The corresponding difference spectra show a remaining signal.

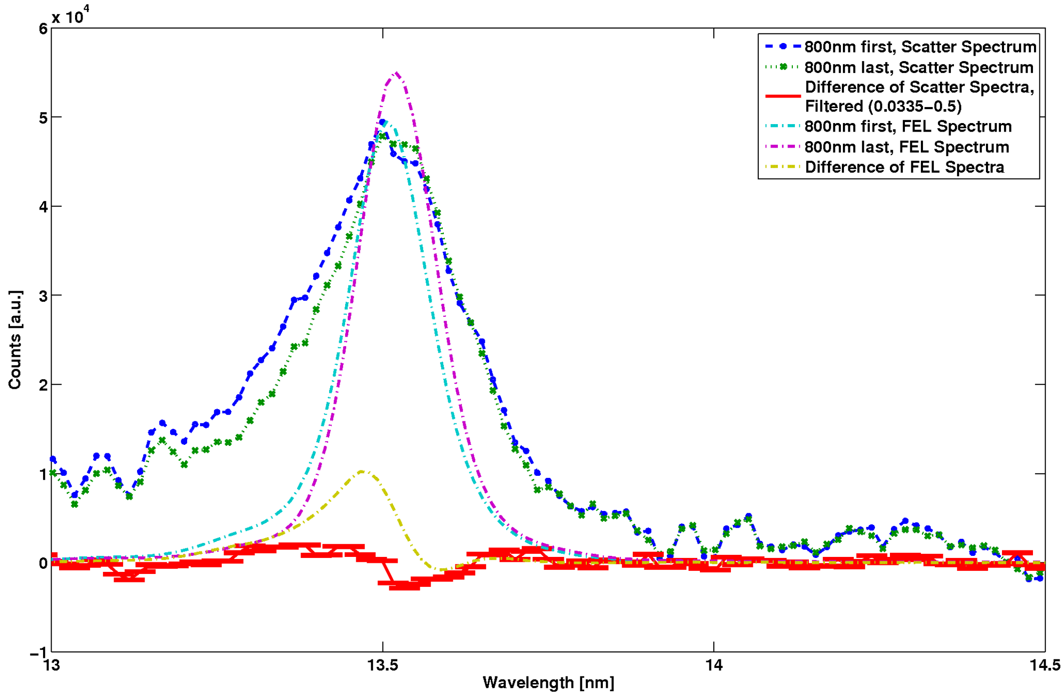

Fig. 5 (colour only in web-version; b/w version available)

Soft x-ray spectra using a 200 nm Zr filter obtained from aluminum following impact of 92 eV FEL radiation (blue line) and of 1.6 eV optical laser radiation (red line). The intensities were 4×10^{14} Wcm^{-2} and 4×10^{15} Wcm^{-2}, respectively.