Note: Study of extreme ultraviolet and soft x-ray emission of metal targets produced by laser-plasma-interaction

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Different metal targets were investigated as possible source material for tailored laser-produced plasma-sources. In the wavelength range from 1 to 20 nm, x-ray spectra were collected with a calibrated spectrometer with a resolution of \( \frac{\lambda}{\Delta \lambda} = 150 \) at 1 nm up to \( \frac{\lambda}{\Delta \lambda} = 1100 \) at 15 nm. Intense line emission features of highly ionized species as well as continuum-like spectra from unresolved transitions are presented. With this knowledge, the optimal target material can be identified for the envisioned application of the source in x-ray spectrometry on the high energy side of the spectra at about 1 keV. This energy is aimed for because 1 keV-radiation is ideally suited for L-shell x-ray spectroscopy with nm-depth resolution.

While increased effort is placed on research for the improvement of large-scale facilities such as synchrotron radiation facilities leading even to novel concepts such as the free-electron-laser, soft x-ray laboratory sources are still not available off-the-shelf. In the laboratory scale mainly plasma sources, either discharged or laser produced, can be used for applications in soft x-ray spectroscopy,1,2 nano-scale imaging,3 or extreme ultraviolet (EUV) metrology.4,5

Discharged based EUV and soft x-ray sources have experienced a great progress in the last ten years but show two issues concerning possible routine usability. Firstly, the source size is relatively large (typically a few 10\( \mu \)m up to 1 mm) reducing the possible spectral brightness and secondly these sources are not easily scalable to photon energies as high as 1 keV.

Laser-produced plasma-sources (LPP) are well established in laboratory x-ray microscopy3,6 and x-ray transmission spectroscopy7 in the water window as well as in EUV metrology.4,5 They exhibit a small source size (typically a few 10 \( \mu \)m) and dependent on the driver laser a sufficient high average power. The latter one is in principle scalable through the repetition rate of the laser. These factors and the possibility to use a broad emission range render LPP sources into interesting x-ray sources, especially in the soft x-ray regime.

For an efficient operation in a wide energetic range, the choice of the optimal target material is crucial. While for the emission of low-Z material intense line emission from highly ionized species is a characteristic property, high-Z material produces a broad continuum-like spectrum. Thus, depending on the requirements posed by the experiment at hand, different target concepts must be chosen.

The use of solid-state metal rods has proven to be a flexible and easy-to-operate concept3 for a broad variety of target materials. When designing a LPP source another important aspect is debris mitigation for the protection of following optics. Numerous mechanisms using magnetic fields,9 gas atmosphere,10 or foil traps11 have already been published which may be combined for optimal operation.

In this short note, we present a study of the x-ray emission of four low-Z metal targets as opposed to the emission of two high-Z targets. The investigated spectral range lies between 1 and 20 nm, respectively 100 to 1200 eV.

In Fig. 1 the setup used in this work is depicted. The laser beam is focussed by an adapted telescope and focussing system onto a rotating and translating metal cylinder. The x-ray emission is detected with a variable line-space (VLS) – grating spectrograph.

The used laser system consists of a regenerative amplifier based on Thin Disk Technology by TRUMPF Inc. The seed pulse is provided by a new type of pulsed Distributed Bragg Reflector (DBR) diode laser, developed by Ferdinand-Braun Institute, Berlin. It delivers output pulses at 1030 nm, with a variable pulse length between 200 ps and a few ns and an output pulse energy of > 250 pJ. The seed pulse is amplified in the regenerative amplifier to pulse energies up to 250 mJ. For the measurements presented below, the laser has been operated at a pulse duration of 1.1 ns, energies up to 250 mJ and a repetition rate of 100 Hz. The variation of laser intensity is smaller than 2% over a time period of 1 h. The focal spot of the laser delivered by the adapted telescope and focussing system is highly symmetric resulting for a pulse energy of 230 mJ in an intensity of about 2 \( 10^{13} \) W/cm\(^2\) on the target. Thus, using a simple blackbody radiation calculation an electron temperature of about 200 eV is estimated.

For intense line emission in the soft x-ray region, we have chosen a cylinder target system with easily exchangeable cylinders made of Cu, Ti, Fe, and Al. These materials were chosen based on tabulated x-ray emission lines derived from the NIST database but also due to their availability, costs, and ease of machining as further criteria. Additionally, Mo and Ag were investigated as targets for broadband emission. In our test setup, the cylinder length of 50 mm and the diameter of 20.5 mm result in a possible operation time of about 3 h. The cylinder was continuously rotated and translated after a few revolutions of the target.

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Telescope lens system
Focussing lens system
Debris filter system
Rotating metall cylinder
Filter and slit
VLS-grating
CCD

FIG. 1. Scheme of the used setup; the laser radiation is focussed onto a rotating and translating metal cylinder, a VLS-grating spectrograph is used for the investigation of the x-ray emission.

For the spectral evaluation of the plasma emission two variable line-space gratings, HITACHI 001–0450 for 1–5 nm radiation and 001–0437 for 5–20 nm, were used. These are aberration-corrected concave gratings, which ensure flat focal planes. The detector was an Andor iDus CCD camera (back-illuminated, thinned CCD, 1024 × 255 pixel, 26 μm size, 16 bit). The spectrograph is equipped with a filter wheel with two filters for the two different gratings (200 nm Al for high photon energies and 220 nm Zr for low photon energies). The efficiency of the gratings as well as the spectral response of the CCD was calibrated by the PTB (Physikalisch-Technische Bundesanstalt) at the synchrotron facility BESSY II. The resolution of the spectrograph was measured to be \( \lambda / \Delta \lambda = 150 \) at 1 nm up to \( \lambda / \Delta \lambda = 1100 \) at 15 nm.

In Fig. 2 spectra of Cu, Fe, Al, and Ti are depicted with the identification of some pronounced lines in the range from 6 to 17 nm. The spectra are composed of a background continuum and line emission as described above. Additionally, the transmission of the Zr filter is depicted in the top graph.

FIG. 2. EUV-spectra taken with the HITACHI grating 001-0437; the transmission of the Zr filter is displayed in the top graph.

In Fig. 3 the corresponding graphs for the region between 1 and 5 nm as well as the transmission of the Al filter are presented. All spectra in Figs. 4 and 5 were taken with a laser pulse energy of 220 mJ and 1 to 10 s exposure time.

Al shows mainly Li- and Be-like ionic emission in both spectral regions, attributed to L-shell bound-bound transitions. Cu, Fe, and Ti being transition metals of the same period show similar behaviour in the XUV region. The

FIG. 3. Soft x-ray spectra taken with the HITACHI grating 001-0450; the transmission of the used Al filter is displayed in the top graph.

FIG. 4. Cu emission spectra measured with the grating for 1–5 nm.
spectra are dominated by Ne-like ionic transitions, with associated satellite lines. In the XUV region, the intense emission of freestanding lines becomes less pronounced from lower to higher-Z elements (Ti to Fe to Cu) due to more possible transitions.

The direct comparison of detected counts and transmissions of the two filters shows, that the emission is more pronounced in the lower energetic region. In the available laser intensity range of these experiments ($5 \times 10^{13} - 2 \times 10^{14}$ W/cm$^2$), the ratio of intensities between lines from different ionization stages does not change significantly.

In Fig. 4 a closer look is taken on the emission of Cu in the range between 1 and 5 nm. The emitted characteristic lines are mainly attributed to Na- and Ne-like species in the plasma. Especially, the use of the triplet (2s$^2$2p$^6$ $-$ 2s$^2$2p$^5$3d) at 1.1383 nm, 1.1594 nm, and 1.1736 nm corresponding to energies between 1056 and 1089 eV is promising for spectroscopic purposes. X-rays with this energy lie in the region of the L-edges of transition metals and can thus optimally excite L-shell emission. As the L-shells are compared to K-shells, more sensitive to the chemical bonding of atoms, the spectroscopic study of transitions involving these shells does not only yield the elemental composition of the sample but as well the chemical environment of a species. Additionally, 1 keV-radiation is ideally suited for nm-depth resolution due to the high absorption compared to hard x-rays.\textsuperscript{13,14}

We have used a pinhole camera combined with Al-foils of varying thickness to estimate the spot size of the source. These estimations yielded a maximal spot size of 35 $\mu$m for the 1 keV region. Based on this value and using the calibrated data for the reflectivity of the grating and for the sensitivity of the CCD camera, brilliance values for the emission lines can be estimated. For the Cu XX line at 1.1594 nm, a brilliance of $>10^{10}$ ph/(mm$^2$ rad$^2$s line) is reached. Using the other metal targets values of $>3 \times 10^{11}$ ph/(mm$^2$ rad$^2$s line) for the water window range as well as for the EUV can be achieved. Using appropriate x-ray optics these brilliances enable a photon flux on the sample comparable to the related values used in soft x-ray spectroscopy at synchrotron facilities.

For comparison Mo and Ag targets as continuum-like emitters were investigated in the 1–4 nm range, only. The spectra are shown in Fig. 5. The broadband emission originates from numerous unresolved lines of ions whose ionization state increases with decreasing wavelength, as can be seen in the Mo spectrum. The transitions can be attributed to Na–Ni-like ions.\textsuperscript{15,16} To the best of our knowledge, no experimental silver spectrum in this energetic range has been published with this resolution before.

In conclusion, different target materials have been investigated and the emitted x-ray spectra have been detected over the wavelength range of 0.8–18 nm. For low-Z material intense line emission can be observed, while for elements with higher atomic weight continuum-like emission is detected.

Based on the quantitative data presented in this work, the brilliance of LPP sources can be tailored according to the envisioned applications. The laser system described above has the advantage of adjustable pulse duration and/or pulse energy corresponding to the desired electron temperature in the plasma. In this way, it is possible to optimize the brilliance of the source for a specific x-ray emission range of interest.

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