Target materials for efficient plasma-based extreme ultraviolet sources in the range of 6 to 8 nm

Alexander von Wezyk¹, Konstantin Andrianov², Thomas Wilhein² and Klaus Bergmann¹

¹ Fraunhofer Institute for Laser Technology ILT, Steinbachstr. 15, 52074 Aachen, Germany
² Institute for X-Optics, Hochschule Koblenz, RheinAhrCampus, Joseph-Rovan-Allee 2, 53424 Remagen, Germany

E-mail: alexander.von.wezyk@ilt.fraunhofer.de, andrianov@hs-koblenz.de, wilhein@hs-koblenz.de and klaus.bergmann@ilt.fraunhofer.de

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Abstract
In a comparative study the extreme ultraviolet (XUV) emission of laser-produced plasmas (LPP) of gadolinium (Gd), terbium (Tb), aluminum (Al), magnesium (Mg) and a magnesium–copper–gadolinium alloy (Mg₆₅–Cu₂₅–Gd₁₀) targets is investigated in order to benchmark the emission potential at a wavelength of around 6.7 nm. Compared to the Gd/Tb targets, the advantage of the alloy is a reduced melting point of $T_m < 500$ °C which leads to the option of a liquid or droplet target system as is usually used for a regenerative target concept. Theoretical considerations are presented to compare the emission potential of the four targets in direct comparison. Experimental results of the LPP are discussed with respect to the 6.6 nm band in order. The measured conversion efficiency of the Mg₆₅Cu₂₅Gd₁₀ target reaches 80% of that of the pure Gd LPP although the Gd fraction is only 2% (atom percent).

Keywords: extreme ultraviolet source, laser produced plasma, 6.6 nm source, diluted target

(Some figures may appear in colour only in the online journal)

1. Introduction

Radiation in the extreme ultraviolet (XUV) region at around 6.6 nm is discussed for the next generation of semiconductor EUV (extreme ultraviolet) lithography after the 13.5 nm technology [1]. The choice of this shorter wavelength is based on the principal availability of multilayer optics with a sufficiently high reflectivity to be used in a high-volume-manufacturing (HVM) system [1, 2]. As one option for the XUV source, a laser produced plasma (LPP) using the rare-earth elements gadolinium or terbium as targets is discussed in the literature [3–6]. These elements are the isoelectronic continuation of tin (Sn), which is used as an efficient emitter at around 13.5 nm.

For these elements the XUV radiation is emitted from unresolved transition arrays (UTAs) resulting from 4d–4f and 4p–4d transitions of highly-ionized ions. The emission resulting from the fourth electron shells is similar to the emission resulting from Sn, but the emission peak is shifted to smaller wavelengths. An example of an efficiently emitting LPP of Gd at around 6.6 nm is given in [6]. Here, the dominant ion-stages are Gd$^{19+}$ to Gd$^{23+}$ at an assumed laser intensity of $(5–10) \times 10^{11}$ W cm$^{-2}$ and an electron temperature of 144 eV. To date, with Gd and Tb a conversion efficiency of up to 0.8% into a 0.6% spectral bandwidth has been reported [7].
LPP sources for 13.5 nm, which are suited to commercial applications, especially in the semiconductor lithography business, use a regenerative target. This is a liquid tin droplet which is irradiated by a laser to produce the EUV emitting plasma [1]. Another source concept is the vacuum spark where tin wetted electrodes, rotating through a liquid tin bath, are used as a regenerative target system in a laser-assisted electrical discharge plasma [8]. Due to the high melting point, of more than 1300 °C, of Gd and Tb compared to the 232 °C of Sn, the handling of a liquid Gd/Tb target appears to be difficult and possibly not suited for later industrial applications. Otsuka et al and Higashiguchi et al compare the plasmas of a pure Gd target and a low density one [4, 5, 9]. It is shown that the absolute emission at around 6. x nm of the plasma does not decrease by using a target with a lowered initial density. This makes Gd- or Tb-containing alloys with lower melting points attractive as future target materials. With respect to the small bandwidth of multilayer mirrors, single resonance line emitters with strong transition at around 6.x nm seem to be attractive as alternative efficient emitters as well. More information about the multilayer mirrors are found, for example, in [10–12].

In this paper we present our theoretical and experimental studies of the emission of 6. x nm radiation emitted from alternative target systems, namely Al, Mg and an alloy composed of Mg, Cu and Gd. Al and Mg have a large number of resonance line transitions [13]. The Mg65Cu25Gd10 alloy is a possible option for a regenerative target system due to a much smaller melting point compared to pure Gd of less than 500 °C. Analog to the studies of alternative target materials, we compare the plasma emission of the alloy with the emission of a pure Gd target.

On the experimental side we record emission spectra of the five plane solid targets Gd, Tb, Al, Mg, and Mg65Cu25Gd10 using a LPP setup. For the sake of availability, we use a laser with a wavelength of 532 nm instead of 1064 nm, which may result in a lower conversion efficiency of the laser power transferred to XUV power. This is investigated by Otsuka et al where the CE in a bandwidth of 2% at 6.7 nm is a factor of 1.6 smaller for the 532 nm wavelength instead of a wavelength of 1064 nm [5]. As known from tin LPPs, an even higher laser wavelength than 1064 nm may be advantageous with respect to optimizing the conversion efficiency [14].

A simple model for plasma radiation is used to judge the emission potential of the elements under consideration rather than only looking at the atomic data for the emission coefficient. This model is also used to estimate the plasma parameters by comparison with the measured absolute emission spectrum.

2. Experimental setup

A scheme of the experimental setup is shown in figure 1. In a vacuum chamber the targets are mounted on an x-y-stage which is moved continuously to provide a fresh and plane target surface for each laser pulse. The laser is a Coherent Infinity 40–100 Nd:YAG which has a primary wavelength of 1064 nm. The second harmonic at 532 nm is generated by conversion of the IR radiation at 1064 nm using a BBO2-crystal [15]. The laser is coupled into the chamber and focused perpendicularly onto the plane solid target with a thickness of several hundred micrometers, and initiates a plasma. The dominant process of the interaction of the laser beam and the target is the inverse bremsstrahlung, where the electrons in the matter are accelerated by the E-field of the laser radiation. This energy is transferred by collisions from the electrons to the ions. The maximum reachable, or so-called critical, electron density only depends on the stimulating laser frequency:

\[ n_c = \frac{m_e e^2 \omega_{laser}^2}{e^2} = 1.11 \times 10^{21} \text{cm}^{-3} \left( \frac{\mu m}{\lambda_{laser}} \right)^2. \] 

Here, \( e \) and \( m_e \) are the electron charge and mass, \( c_0 \) is the permittivity in vacuum, \( \omega_{laser} \) and, \( \lambda_{laser} \), are the laser frequency and laser wavelength, respectively. The electron density in the plasma reaches values close to the critical electron density. For a wavelength of 532 nm the critical electron density is \( 3.9 \times 10^{19} \text{ cm}^{-3} \). The laser pulse length is 2.4 ns at the full width half-maximum (FWHM), which is also experimentally checked using a Hamamatsu S1722 photodiode. A maximum laser pulse energy of 140 mJ at the position of the targets is measured with a laser power meter. The laser pulse duration and energy in combination with focused laser spot (diameter 40 μm) lead to a focal intensity of \( 4.8 \times 10^{12} \text{ W cm}^{-2} \).

The plasma emission is analyzed using a flat field grazing incidence spectrometer and an inband energy monitor. Both are mounted under an observation angle of roughly 45° to the normal of the target. Furthermore, in an additional experiment the plasma source size is measured using a Schwarzschild inband XUV camera [16].

The flat field grazing incidence spectrometer, including the grating with 1200 lines mm⁻¹, is designed for the spectral range between 5 and 20 nm. The detector is an Andor back-illuminated cooled CCD with 1024 × 1024 pixels and a pixel size of 13 μm. The spectral resolution at a wavelength of 6.7 nm is determined to be \( \lambda/Δ\lambda = 140 \), depending on the size of the used entrance slit of 100 μm. To suppress laser and other out-of-band radiation a zirconium foil (Zr) of 200 nm thickness is used as a spectral filter. Further information about the grating, the flat field grazing incidence spectrometer and the camera can be found in [17–20].

The inband energy monitor consists of a 45° LaB6-C-ML mirror, a Zr foil and a Hamamatsu S1722 photodiode. The 45° LaB6-C ML is designed for a central wavelength of 6.7 nm with a maximum reflectivity of 34% for unpolarized XUV radiation. The spectral bandwidth (FWHM) is 1.7% (0.113 nm at 6.7 nm). The 200 nm thick Zr foil is again used as spectral filter. The energy monitor is calibrated against another ML tool, consisting of two ML mirrors and a spectral bandwidth of 0.5% at 6.7 nm at a gas discharge source. More details on these monitors and the calibration are given in [16, 21].

To determine the plasma source size at 6.x nm an inband XUV camera is used. The inband XUV camera consists of a 200nm thick Zr foil, used as spectral filter for laser radiation, two spherical multilayer mirrors in a Schwarzschild configuration and a CCD coated with a scintillator for the conversion of XUV to visible light. The pixel size of the CCD is...
6.45 × 6.4 µm². The mirrors are made, analog to the ones of the energy monitor, of La/B₄C layers. The magnification of the camera is $M = 9$, which results in a resolution of down to $\Delta x = 2 \mu m$ for the used pixel size. Further information about the ML tool and the XUV inband camera can be found in [16].

Simultaneous measurements of the inband energy and the emission spectrum allow us to determine an absolute scale on the spectra. The simultaneous measurement also allows us to determine the absolute brightness measured with the XUV inband camera.

### 3. Target materials

We study the emission of radiation in the wavelength range between 4 and 9 nm with a special interest in the wavelength at 6.6 nm. For this we use a laser-produced plasma of the five solid targets: Gd, Tb, Al, Mg and an alloy consisting of Mg₆₅Cu₂₅Gd₁₀. The Gd spectrum is used as a reference to compare our results to published ones and also with the spectra of the other four targets. Al and Mg seem to be suitable emitters due to a sufficiently high number of transition lines in the spectral region of 6.6 nm when looking at the atomic data for the spectral range of interest [13]. The ionization levels Al VIII to Al IX and Mg VIII to Mg IX are identified as the most important ions contributing to 6.6 nm emission. For the wavelength interval between 6 nm and 7 nm, 200 transitions of Al are identified and around 110 for Mg, respectively.

The transition probabilities $g_A a_A$ (the product of the statistical weight of the lower energy level and the Einstein coefficient for spontaneous emission) of Al and Mg are typically one order of magnitude lower compared to the ones for Gd and Tb [13, 22, 23].

The lower melting point of Al (660 °C) and Mg (650 °C) compared to Gd/Tb, and the opportunity of using alloys with even lower melting points, make these elements attractive from a technological point of view.

The Mg₆₅Cu₂₅Gd₁₀ alloy is a first approach to evaluate a target system based on a lanthanide but with optimized chemical properties, in particular a reduced melting point. Compared to pure Gd, which has a melting point of $T_m = 1312$ °C, the one of the alloy at $T_m < 500$ °C [24] enables the option to get a liquid target to load droplet generators or liquid wetted carrier systems. A Mg₆₅Cu₂₅Gd₁₀ alloy has been fabricated at Mimitech—Metallurgical Innovations and Materials for Industrial Technology Improvement, Aachen, Germany. The expected melting point taken from phase diagrams has been verified experimentally by monitoring a cooling curve of such a sample. Starting at 600 °C, in the liquid phase, and letting it cool down to 400 °C in a time interval of 1000 s, the temperature decrease shows characteristic deviations from a linear behavior (=lower slope in the temperature decrease) around 500 °C, 463 °C and 429 °C [16]. At these temperatures the phase configuration changes to being in the liquid phase above 500 °C.

Following the research presented in [4–6, 25] and our own calculation presented in section 4, it can be shown that the dilution of the emitter by mixing it with bulk materials has not lead to significant losses in emissivity. The number of Gd atoms in comparison to a pure Gd target is reduced by a factor of 50 with the Mg₆₅Cu₂₅Gd₁₀ alloy.

### 4. Plasma emission model

A simple model is presented, which allows for the estimation of the emission potential of different elements in the XUV which are in a plasma state with reasonable plasma parameters. The model takes into account resonance line transitions and also overlapping transitions (UTAs) as present for Gd and Tb. Reabsorption processes affecting the optical thickness and the level population are included as well.

Generally, the spectral brightness of a plasma can be calculated by using the radiation transport equation

$$\frac{dL(s, \lambda)}{dz} = j(s, \lambda) - \chi(s, \lambda) \cdot L(s, \lambda)$$  \hspace{1cm} (2)

with the emission coefficient $j(s, \lambda)$ and the absorption coefficient $\chi(s, \lambda)$ [26]. Assuming a homogeneous plasma medium
along the observation axis, s, and an expansion, d, of the plasma, the spectral brightness $L(\lambda)$ is given by the integration of the homogeneous radiative transport equation:

$$L(\lambda) = \frac{j(\lambda)}{\chi(\lambda)} \left(1 - e^{-\tau(\lambda)}\right)$$  \hspace{1cm} (3)

with the optical thickness $\tau(\lambda) = \chi(\lambda) \cdot d$. The parameters $j(s, \lambda)$, and $\chi(s, \lambda)$ can be expressed as follows:

$$j(\lambda) = \sum_i j_i(\lambda) = \sum_i \frac{hc}{4\pi\lambda} A'_{li} n_{li} f'(\lambda)$$  \hspace{1cm} (4a)

$$\chi(\lambda) = \sum_i \chi_i(\lambda) = \sum_i \frac{h\lambda}{c} (B'_{li} n_{li} - B_{li} n_{li}) f'(\lambda)$$  \hspace{1cm} (4b)

where $B_{li}$, $A_{li}$, $B'_{li}$ are the Einstein coefficients for absorption, spontaneous and stimulated emission, $n_{li}, n_{li}$ the ion densities of the lower (l) and upper (u) level of the considered transition, $i$, $h$ and $c$ are the Planck constant and the speed of light in a vacuum and $f'(\lambda)$ the line profiles for each atomic transition $i$. The same line shapes are assumed for emission and absorption for the present considerations.

The Einstein coefficients relate to each other as follows:

$$B_{lu} = B_{ul} \frac{g_u}{g_l} = \frac{\lambda^3}{8\pi^2} A_{ul} \frac{g_u}{g_l}$$  \hspace{1cm} (5)

with $g_l$ and $g_u$ the statistical weights ($g_{ul} = 2J_{ul} + 1$ with $J$ the total angular moment) of the lower and upper level. The index, $i$, is here omitted for the sake of readability.

The line profile $f'(\lambda)$ depends on the electron density in the laser-produced plasma. With equation (1) the electron densities of an LPP is usually in the range of $n_e \approx 10^{21}$ cm$^{-3}$. Due to complex broadening effects, the line broadening cannot be determined easily. In the literature typical values of around $\Delta\lambda = 0.0035$ nm are reported for AI [27]. Estimation of Doppler and collisional broadening using simplified formulas for hydrogen-like ions [28] leads to similar values. Due to the uncertainties in the knowledge of the absolute plasma parameters, the line broadening is set to a fixed value of $\lambda/\Delta\lambda = 3000$ for the presented simulations.

An approximation for the ratio of the level population of upper and lower levels assuming a steady state, i.e. $dn_{li}/dt = dn_{ul}/dt = 0$. Furthermore, only transitions between these two levels are taken into account, namely electron excitation and de-excitation spontaneous emission and absorption. Thus, the population fraction between the lower and upper level can be expressed as [29]:

$$\frac{g_{ul} n_{li}}{g_{li} n_{ul}} = e^{\Delta E/T_e} \cdot \left(1 + 2.7 \cdot 10^{15} \frac{g_i}{n_i c m^3} \left(\frac{\Delta E}{eV}\right)^3 \frac{T_e}{eV} \right).$$  \hspace{1cm} (6)

At large electron densities the second part of equation (6) becomes small and equation (3) approaches the spectral radiance of a Planck radiator, $L_{\text{Planck}}(\lambda) = (2hc^2/\lambda^5) \cdot (e^{\Delta E/T_e} - 1)^{-1}$, if $\tau(\lambda) \gg 1$. The effect of self-absorption on the level population and the influence of the spectral radiance is described by the Holstein escape factor $g(\tau_m)$ in equation (9). The Holstein escape factor for a Gaussian line shape $f'(\lambda)$ can be approximated for a multi-level ion as [16]:

$$g(\tau_m) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} e^{-x^2} \cdot e^{\tau_m x} dx$$  \hspace{1cm} (7)

with:

$$\Delta^d = \frac{\lambda^d - \lambda^l}{\Delta\lambda} \cdot \sqrt{4 \cdot \ln 2}.$$  \hspace{1cm} (8)

To determine the minimum electron temperature required to reach the relevant ionization levels, the distribution of ions of the charge Z as a function of the electron temperature at the critical electron density can be calculated from the rate equations for the ionization and recombination processes.

In the collisional radiative (CR) model which describes a LPP [30], considering the collisional ionization $\tau_{ion^{-1}}$, radiative recombination $\tau_{rad-rec}^{-1}$ and three-body-recombination $\tau_{3b-rec}^{-1}$ rate coefficients, the ion distribution is given by:

$$\frac{N_{Z+1}}{N_Z} = \frac{\tau_{ion}^{-1}}{\tau_{rad-rec}^{-1} + \tau_{3b-rec}^{-1}}$$  \hspace{1cm} (9)

with the ionization levels $N_Z$ and $N_{Z+1}$ of charge $Z$ and $Z + 1$, respectively. The rate coefficients are taken from [26]:

$$\tau_{ion}^{-1} = 2.4 \cdot 10^{-6} \cdot \text{cm}^3 \text{s}^{-1} n_e \cdot \frac{g_i}{g_l} \cdot \frac{T_e^{1/4}}{T_e^{7/4}} \cdot e^{-\frac{\Delta E}{T_e}}$$  \hspace{1cm} (10a)

$$\tau_{rad-rec}^{-1} = 4 \cdot 10^{-28} \cdot \text{cm}^3 \text{s}^{-1} \cdot \frac{g_i}{g_l} \cdot \frac{T_e^{1/4}}{T_e^{7/4}} \cdot \frac{n_e^2}{\chi_i} \cdot \frac{T_e^{5/4}}{T_e^{8/4}}$$  \hspace{1cm} (10b)

$$\tau_{3b-rec}^{-1} = 9.6 \cdot 10^{-14} \cdot \text{cm}^3 \text{s}^{-1} \cdot n_e Z_i^2 \cdot \frac{T_e}{T_e} \cdot \sqrt{\left(\ln\frac{\chi_i}{T_e}\right)^2 + 2}$$  \hspace{1cm} (10c)

where $\chi_i$ is the number of electrons on the outermost shell, $\chi_i$ is the ionization energy and $Z_i$ is the atomic number of the neutral atom.

Solving the system of equations (9) and (10a)–(10c) the typical electron temperatures for Al VIII to Al IX and Mg VIII to Mg IX plasmas at an electron density of $3.9 \times 10^{23}$ cm$^{-3}$ result between 35 eV and 70 eV.

The ions of Gd and Tb which contribute to 6.8 nm radiation cannot be assigned to two or three ionization stages. In the literature the identified ions range from Gd XIX/Tb XX to Gd XXVIII/Tb XXIX [6, 22, 23]. Depending on this wide range, the electron temperature is also widely spread. Typically, the emission of Gd and Tb is attributed to $Z \approx 20$, so that an electron temperature of more than 100 eV is needed.

Equation (3) depends on the ion density of the lower level ($n_{li}$). The ion density is estimated by the charge Z of the ion and the degeneracy of the energy levels inside each charge state:

$$n_i' = n_i Z_i \cdot \frac{g_i'}{\sum_k g_k'} \cdot e^{-\frac{\Delta E_k}{T_e}}$$  \hspace{1cm} (11)
\[ \text{ne} = \sum n_i Z \cdot Z. \]

For the identified lines of Al and Mg it is possible to estimate the ion density using equation (11) because for all considered transitions the statistical weights are given. For Gd and Tb these values are not available so the degeneracy of the energy levels is assumed by the square root of the number of transitions, which is typically 20 to 25.

The atomic data required for the simulations are in particular \( \lambda_0, A_{\text{ul}}, g_u, g_l \) or \( g_l A_{\text{ul}} \). The data for Al and Mg are taken from the NIST database and the Gd and Tb data are provided from G O’Sullivan and D Kilbane who calculated the transitions using some atomic codes [13, 22, 23].

As an example of the comparison between gadolinium and aluminum, synthetic spectra are shown in figure 2. The emission is restricted to only one ionization level for each case, (a) Gd XXIII and (b) Al VIII. The electron density of \( \text{ne} = 3.9 \cdot 10^{21} \text{cm}^{-3} \), \( T_e = 100 \text{ eV} \) and \( d = 10 \mu \text{m} \).

The calculations for Tb and other ionization of Gd levels show the same behavior, qualitatively. This is also true for Mg and Al. For these plasma parameters the optical thickness of Gd is typically one order of magnitude higher than for the Al and Mg. A reduction of ion density is expected to lead to lower emission for Al and Mg. For Gd and Tb it will still lead to optical thick emission close to the blackbody limit. This is shown in figure 2(c) where synthetic spectra of pure Gd XXIII (black) and a diluted 5% Gd target (red) are compared for the same plasma parameters as used above. In this model only one ion (Gd XXIII) is considered and also the influence of the bulk material, i.e. contributions and interaction with other ionization levels of different elements, is neglected. In the case of elements, which anyway have a much lower number

![Figure 2. Simulation of the spectral radiance of one ion stage for (a) Gd XXIV, (b) Al VIII and (c) 100% Gd XXIV (black) and 5% Gd (red); ne = 3.9 \cdot 10^{21} \text{cm}^{-3}, T_e = 100 \text{ eV} \text{ and } d = 10 \mu \text{m}.](image)
of transitions compared to Gd, this will be justified. The factor of dilution is 20 and much bigger compared to the predicted radiation losses. For the diluted target the maximum emission also reaches values close to the Planck limit, where the optical thickness of the UTAs are high enough. The qualitative prediction for the comparison of Gd, Tb, Al and Mg will now be compared with experimental results.

5. Experimental results

LPP emission spectra of the four pure emitter elements (a) Gd, (b) Tb, (c) Al and (d) Mg are shown in figure 3. The laser pulse energy is 140 mJ in all cases. The absolute wavelength calibration is determined from atomic data for Al and Mg from the NIST database. The resulting dispersion relation based on these atomic data is then applied to the Gd and Tb spectra.

According to [6, 22] the contributing ionization stages are attributed to Gd XIX—Gd XXVIII. The lines result in the unresolved transition arrays (UTA) of the fourth electron shell 4d–4f and 4p–4d. Analogously, the Tb emission is assumed to result from Tb XX–Tb XXIX transitions.

Both Al (c) and Mg (d) persist on a large, but resolvable, number of emission lines resulting from atomic transitions dominated by 3p–2p (Al) and 3d–2p (Mg). For Al the main contribution ions to 6.7 nm emission are identified as Al VIII and Al IX. Respectively, for Mg this is Mg IX and Mg X, based on a comparison with the atomic data.

Table 1 summarizes the measured absolute inband XUV energy, peak energy and the conversion efficiency for all four elements. Al and Mg are analyzed at the next emission line close to 6.7 nm. Gd and Tb are analyzed at the typical 6.7 nm and Gd additionally at the maximum value, to get the maximum efficiency. In good agreement with published values [5], the CE of Gd at 6.7 nm is 0.28%/2π sr for a laser wavelength at 532 nm. The conversion efficiency of Tb also is 0.28%/2π sr. The source profile of the Gd plasma is measured with the Schwarzschild XUV inband camera. The measured rotation-symmetric source profile has a diameter of around 43...
μm (FWHM) which is close to the focal spot size of the laser. The brilliance, calculated from the camera image and the energy measurement, is determined to be \(22 \text{ mJ sr}^{-1} \text{ mm}^{-2}\) into a spectral bandwidth of 0.6%.

The measured spatial inband emission profiles of the different target materials show the same diameter for all targets and an angular dependence, which is consistent with the assumption of a thin disk plasma [16]. The thickness is much lower than the diameter, which is determined by the laser focal diameter. In conclusion, the plasma parameters relevant for the XUV emission can be regarded as mainly determined by the laser parameters rather than being influenced substantially by the hydrodynamic expansion, which could differ for the materials under consideration. With the disk shape emission volume, opacity effects on the angular emission characteristics are especially expected for radiation with low opacity. Based on the theoretical considerations, the opacity will cover a broad range for all elements. A detailed analysis of the angular emission characteristics will be discussed elsewhere. Keeping the observation angle constant for all elements implies the best approach to provide similar plasma conditions for all elements.

Due to the small usable bandwidth of available ML-mirrors, the 6.7 nm narrowband line emission of Al and Mg is attractive, but at a slightly shifted wavelength. Both Al and Mg have a CE of 0.18%/2πsr which is more than 50% compared to the broad emitters, Gd and Tb. The much-reduced melting point is an advantage compared to Gd and Tb, from a technological point of view.

In figure 4 the emission spectra of the Cu65Mg25Gd10 alloy and the pure Gd are shown for the same laser pulse energy of 80 mJ in direct comparison. The alloy reaches 80% of the inband emission energy of the pure Gd target although the dilution is a factor of 50. In addition to the pure Gd emission, the alloy also exhibits transitions from Mg in the spectral range of interest. The average broad spectral behavior of Gd can be identified to be roughly 40% to 50% of that of the pure Gd. At the characteristic spectral lines of Mg the emission is increased due to a superposition of the Gd and Mg emission. At 6.72 nm the Mg emission line increases the emission almost to the emission of the pure Gd target. At the wavelength of 6.72 nm the peak energy of both spectra is 0.65 mJ (sr nm)\(^{-1}\). For the wavelength 6.72 nm the XUV inband energy is 20.8 ± 0.8 μJ sr\(^{-1}\) for the alloy and 24.9 ± 0.9 μJ sr\(^{-1}\) for pure Gd in a spectral bandwidth of 0.6%.

In table 2 some other alternative alloys are listed. The melting points are equal or less than 700 °C and therefore roughly a factor of two smaller than Gd or Tb. The Gd portion is higher compared to the studied alloy, so with the experimental result in figure 2(c) it should be possible to increase the emission close to the emission of pure Gd if a less diluted target is used.

### Table 2. List of Gd-/Tb-based alloys with Gd or Tb portion and melting temperatures [24].

| Alloy            | Melting point °C | Gd or Tb portion % wt |
|------------------|------------------|-----------------------|
| Ni6Gd96          | 640              | 69.0                  |
| Mg62Gd28         | 550              | 19.9                  |
| Mg65Cu25Gd10     | 486              | 2.0                   |
| Mg60Tb20         | 550              | 21.2                  |
| Co37.5Tb62.5     | 700              | 38.2                  |

### 6. Comparison of experimental and simulated Al and Mg spectra

To get a better understanding of the plasma state, the measured Al and Mg plasmas are compared to synthetic spectra based on the model in section 4. The parameters of electron temperature and ionization level distribution are varied in order to get a reasonable fit with the measured data. The duration of emission is set to be given by the laser pulse duration of 2.4 ns.

Figures 5(a) and (b) show the results for Al and Mg of the experimental spectra (top) compared to the simulated ones (bottom). The used electron temperatures and ion distribution for each recognized ion species are given in table 3. The electron temperatures are in the range of 45 to 77 eV for both elements. These values are in good agreement with the electron temperatures between 35 and 70 eV calculated with the system of equations (9) and (10a)–(10c). The assumption of different electron temperatures for the ionization levels may be justified assuming a transient, nonequilibrium behavior of the plasma during the XUV emission. The attributed electron temperature is in any case in the range where the maximum abundance of the observed ionization levels is expected. It has to be emphasized that a good agreement of the measured and synthetic spectra can be achieved although the underlying model is rather crude. The prediction of the achieved temperature range should be justified using this method. It further shows that the achieved parameters are in a reasonable range for efficiently exciting 6.7 nm radiation from the used

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**Figure 4:** Measured emission spectra of Cu65Mg25Gd10 alloy (black) and Gd (red) at a laser pulse energy of 80 mJ.

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**Table 2:** List of Gd-/Tb-based alloys with Gd or Tb portion and melting temperatures [24].
Conclusion

In addition to the well-known emitters Gd and Tb for intensive radiation in the range of 6 to 8 nm, we identified and investigated Al and Mg as possible intensive line emitters and diluted Gd- and Tb-based alloys, which have the potential to achieve a comparable spectral brightness in laser-induced plasmas.

Table 3. Electron temperature (\(T_e\)) and ion distribution of the simulated emission spectra for Al and Mg shown in figure 5.

| Ion  | Al VI | Al VII | Al VIII | Al IX | Al X | Al XI |
|------|-------|--------|---------|-------|------|-------|
| Portion [%] | 4.1 | 6.9 | 34.2 | 27.4 | 13.7 | 13.7 |
| \(T_e [\text{eV}]\) | 55 | 55 | 59 | 62 | 66 | 77 |

| Ion  | Mg VI | Mg VII | Mg VIII | Mg IX | Mg X | Mg XI |
|------|-------|--------|---------|-------|------|-------|
| Portion [%] | 11.5 | 11.5 | 23.5 | 34.8 | 17.5 | 1.2 |
| \(T_e [\text{eV}]\) | 45 | 50 | 54 | 62 | 75 | 75 |

Figure 5. Measured (top) and simulated (bottom) emission spectra for Al (a) and Mg (b).
These materials may be suited to a regenerative liquid target in future sources with high long term stability and high average brightness. The conclusion is based on the theoretical prediction of the brightness based on a model which allows for the estimation of the plasma emission at typical plasma parameters for such laser-induced plasma sources, and experimental results with direct comparison of the target emission.

A variety of alloys are identified (table 3) which will have a melting point below 700°C, which is much lower compared to ~1300°C of pure Gd. The emission of strongly diluted Cu₆₆Mg₂₃Gd₉₀ alloy with a melting point below 500 °C has been presented, which exhibits around 50% of the broadband and roughly the same brightness in selected spectral intervals at around 6–8 nm compared to pure Gd.

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**ORCID iDs**

Klaus Bergmann [https://orcid.org/0000-0002-4483-8943](https://orcid.org/0000-0002-4483-8943)

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