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# The effect of viewing angle on the spectral behavior of a Gd plasma source near 6.7 nm

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## **Abstract**

We have demonstrated the effect of viewing angle on the extreme ultraviolet (EUV) emission spectra of gadolinium (Gd) near 6.7 nm. The spectra are shown to have a strong dependence on viewing angle when produced with a laser pulse duration of 10 ns, which may be attributed to absorption by low ion stages of Gd and an angular variation in the ion distribution. Absorption effects are less pronounced at a 150-ps pulse duration due to reduced opacity resulting from plasma expansion. Thus for evaluating source intensity it is necessary to allow for variation with both viewing angle and target orientation.

High temperature laser produced plasmas are expected to provide the optimum source of high efficiency extreme ultraviolet (EUV) radiation for extreme ultraviolet lithography (EUVL). In particular, laser produced tin plasmas have been shown to be the highest brightness sources of radiation at 13.5 nm. The most promising configuration for EUVL at this wavelength is based on having a Nd:yttrium-aluminum-garnet (Nd:YAG) laser prepulse, with an energy of a few mJ, irradiate a droplet target to produce a plasma which is subsequently reheated by short pulse CO<sub>2</sub> laser irradiation. This setup has been shown to yield high conversion efficiency, when the pre-plasma has expanded to match the system etendue and the density is such that radiation trapping is minimized, and also to permit high repetition rates. With the situation at 13.5 nm well understood, laser produced plasmas that have high intensity emission below 10 nm have now become the focus of interest to developers of next generation EUVL tools.

EUV radiation emitted from laser produced gadolinium (Gd) plasmas may in future be used with La/B<sub>4</sub>C multilayer mirrors to produce a viable source for EUVL at 6.x nm. The precise value of x is yet to be determined but will be decided by the source and reflectivity combination that provides the brightest in-band EUV yield and conversion efficiency. Recent theoretical work has proposed 6.76 nm as the optimum choice for the location of the reflectivity peak of EUV optics in a future lithography system based on the fact that the strongest lines observed in this region originate from Ag- and Pd-like ions [1-3]. Previous experimental work [4-6] has shown the spectral and in-band intensity dependence of Gd plasmas on laser wavelength, intensity and target composition and concentration. Spectra from pure Gd targets in the 6.7 nm region were shown to be optically thick, however, the opacity could be reduced by decreasing the Gd concentration or increasing the laser wavelength [5,6]. As the ion stages involved in the 6.x nm radiation from Gd plasmas are higher than those of the 13.5 nm emitting ions of Sn plasmas, higher electron temperatures

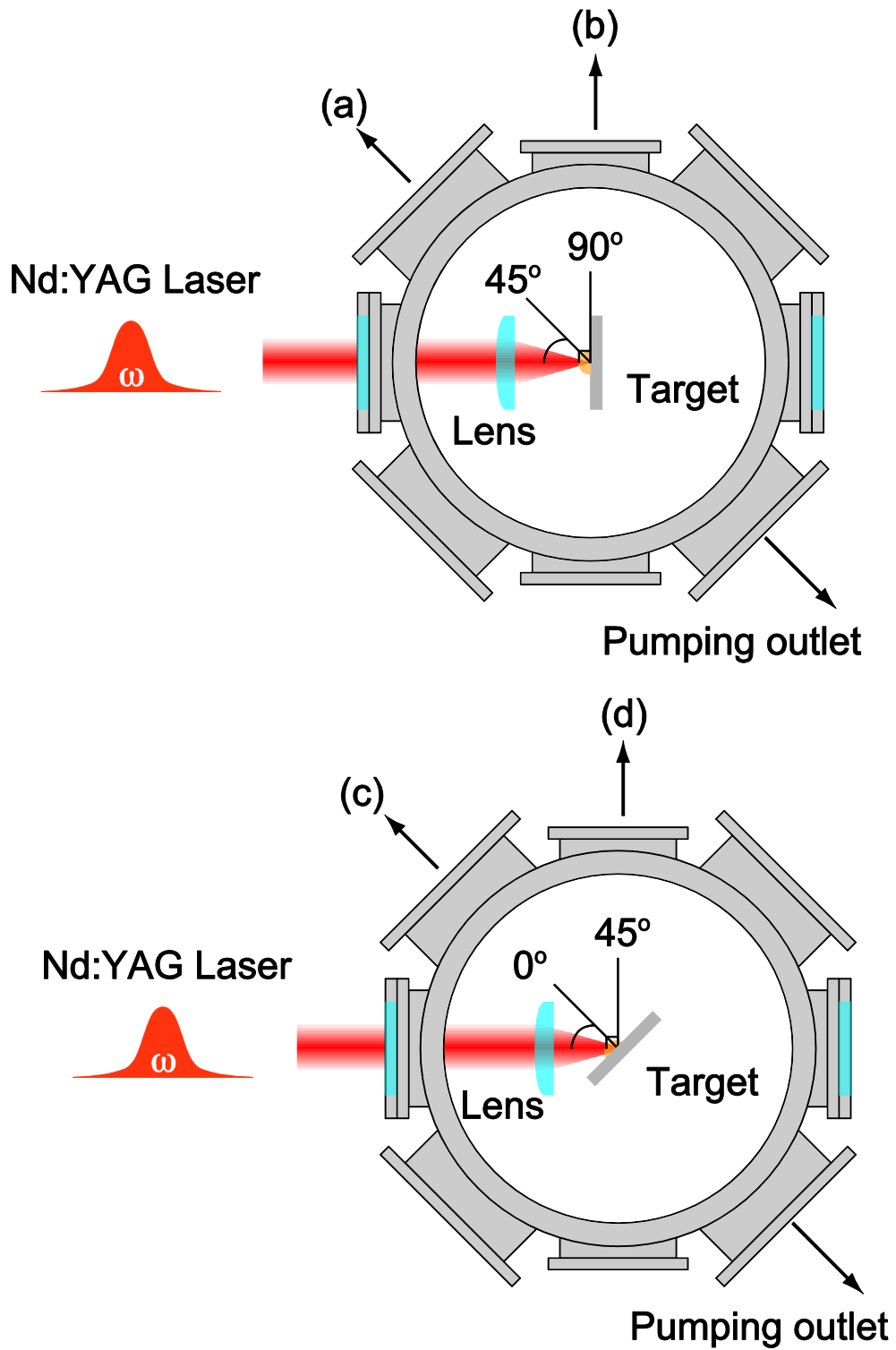
are needed and thus higher laser power densities. The ion stage distribution and density thus play a crucial role in the transport of radiation through the plasma due to opacity effects. Their distribution strongly depends on experimental conditions, such as laser wavelength, laser pulse duration, focal spot size and target geometry. We focus on the spectral behavior of Gd plasmas as a function of laser pulse duration and viewing angle by using 150 ps and 10 ns laser pulse durations, respectively, to irradiate the target. The change in laser pulse duration results in a change of optical thickness, that is, the self-absorption length due to the different conditions in the EUV emitting regions of both sets of plasmas. From the point of view of optimization of a Gd plasma EUV source, we measure and compare the spectral behavior at different viewing angles and different incident angles of the laser pulse with respect to a planar target.

For the optimization of an EUV source, accurate measurement of the conversion efficiency is a critical issue. A typical experimental setup consists of a laser irradiating a target at either  $45^\circ$  or normal incidence and measurements being taken at one fixed angle with respect to the laser beam direction. This measurement, assumed to be independent of viewing angle, is then used to estimate the total, collectable in band EUV energy and from this value the conversion efficiency is calculated. As was shown previously for Sn LPPs [7-9], this method is inappropriate as the EUV emission is anisotropic both in terms of spectral profile and in-band intensity and consequently the variation with viewing angle of the plasma emission must be taken into account.

In this letter, we demonstrate the effect of viewing angle on the spectral emission of laser produced Gd plasmas that are irradiated normally and at  $45^\circ$  with two different laser pulse durations. We show the effect of two-dimensional plasma expansion on their emission spectra. In particular, we see a large anisotropy in the spectral emission from plasmas produced with a pulse duration of 10-ns. We show how the use of short pulse durations or low

density targets can significantly reduce this anisotropy. We further demonstrate the importance of considering the angular variation of absorption effects in the modeling of optically thick plasmas.

Nd:YAG lasers operating at  $\lambda=1064$  nm produced maximum pulse energies of 180 and 360 mJ with a pulse duration of 150 ps and 10 ns [full width at half-maximum (FWHM)]. The lasers were focused onto the target with a 10-cm focal length lens. The focused laser power density was varied from  $10^{11}$  to  $10^{14}$  W/cm<sup>2</sup> at a constant focal spot size of 30–40  $\mu$ m (FWHM). To achieve a range of laser power densities, the output energy was varied keeping the focal spot size constant. Two target orientations were used, illustrated in [Fig. 1](#). For each target geometry two viewing angles were used for measurement. Plasmas were formed on the optical axis of a flat field grazing incidence spectrometer housing a 2400-grooves/mm variable line space grating. Time-integrated spectra were recorded by a thermoelectrically cooled back-illuminated x-ray charge coupled device (CCD) camera.



*Fig 1: Schematic diagram of the experimental setup showing the two target geometries used and the different detection angles.*

Figure 2 shows the effect of viewing angle on the emission spectra for both target geometries for both 10-ns and 150-ps pulse durations. In both sets of spectra, the presence of emission from Ag- and Pd-like  $Gd^{17+}$  and  $Gd^{18+}$ , which gives rise to resonance lines near 6.76 and 7.14 nm is clearly evidenced by small intensity peaks in all of the spectra shown in this figure. The spectrum produced by the 10 ns laser pulse is optically thick [10-12]. For normal incidence laser irradiation, the spectrum viewed at  $45^\circ$  shows less evidence of absorption at longer wavelengths than that viewed along the surface of the target. As described by Filevich *et al.* [13], EUV emission from laser-produced plasmas creates a cold plasma on the target surface dominated by low ion stages. As the photoabsorption profile of neutral to 3 times ionized Gd consists of giant resonances in the 7–9 nm range with cross sections up to tens of Mb [14-16], radiation trapping by low ion stages may considerably reduce the observed intensity in this region.

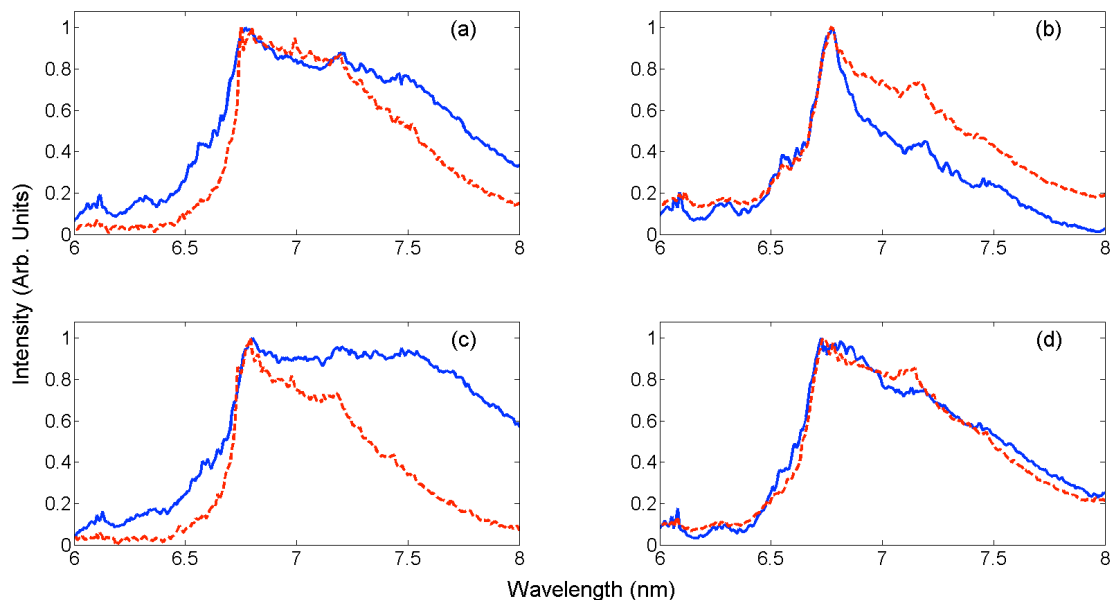


Fig 2: Emission spectra from the 10 ns (blue, solid line) and the 150 ps (red, dashed line) LPPs for the four different viewing angles, illustrated in Fig. 1.

To test this hypothesis, spectra were also obtained with the 10-ns laser from a foam target with a 30% composition of Gd by mass, known to produce spectra that are optically thinner [6]. The results are presented in Fig. 3 for the observation scheme of Fig. 2(b). It is clear that the spectrum from the foam target is more intense in the longer wavelength region indicating that absorption is indeed present for the pure target. For the plasma viewed at the orientations of Fig. 2(c) and 2(d), because of opacity effects, the bulk of the observed emission is known to originate in a layer close to the plasma boundary and the ion distribution there largely controls the emission profile [17]. For an expanding plasma, the highest stages are generally found close to the centre of the plume while lower stages dominate close to the edge. Fig. 2(c) has a larger long wavelength component than any of the other spectra recorded at 10 ns duration which could arise from three possible effects, either individually or in combination. Firstly, it could reflect the presence of emission from ion stages higher than  $Gd^{18+}$  as their resonance emission moves to longer wavelength with increasing charge. Secondly, emission from satellites also contributes on the long wavelength side of the parent one electron transition, and thirdly emission from lower stages that is less affected by absorption. For all of these effects, in the irradiation scheme of Fig. 2(c) and 2(d) plasma expansion is observed to be directed either along the target normal or at an angle intermediate between the target normal and the incident laser beam. Thus in Fig. 2(c) the plasma is being viewed along the direction of the highest charged ions. The explanation of the spectrum of Fig. 2(d) appears less clear, certainly emission from  $Gd^{17+}$  and  $Gd^{18+}$  is present and the contribution from higher stages and satellites is less than for Fig. 2(c). For expansion along the target normal, the spectra shown in Fig. 2(d) should be similar to that of Fig. 2(a) as both are observed at  $45^\circ$  to the target normal. However this spectrum was found to vary from shot to shot. This behavior is most likely due to variations in small features on the

surface changing the angle of plasma expansion. Full hydrodynamic modeling is required to resolve these differences.

Figure 2 also shows the emission spectra of the Gd plasma produced by a laser pulse width of 150 ps. These spectra do not change as significantly as a function of viewing angle compared with spectra generated by the 10-ns pulses, however absorption is still present as evidenced by changes in spectral profile particularly evident in Fig. 2(a) and 2(b). In this case emission comes from an expanding plasma in which the emitting region is at a lower density. Thus radiation trapping is less important. In particular, the spectral profiles in Figs 2(a) and 2(d) are similar indicating that in the case of sub-nanosecond irradiation, the plume expansion is indeed directed along the target normal.

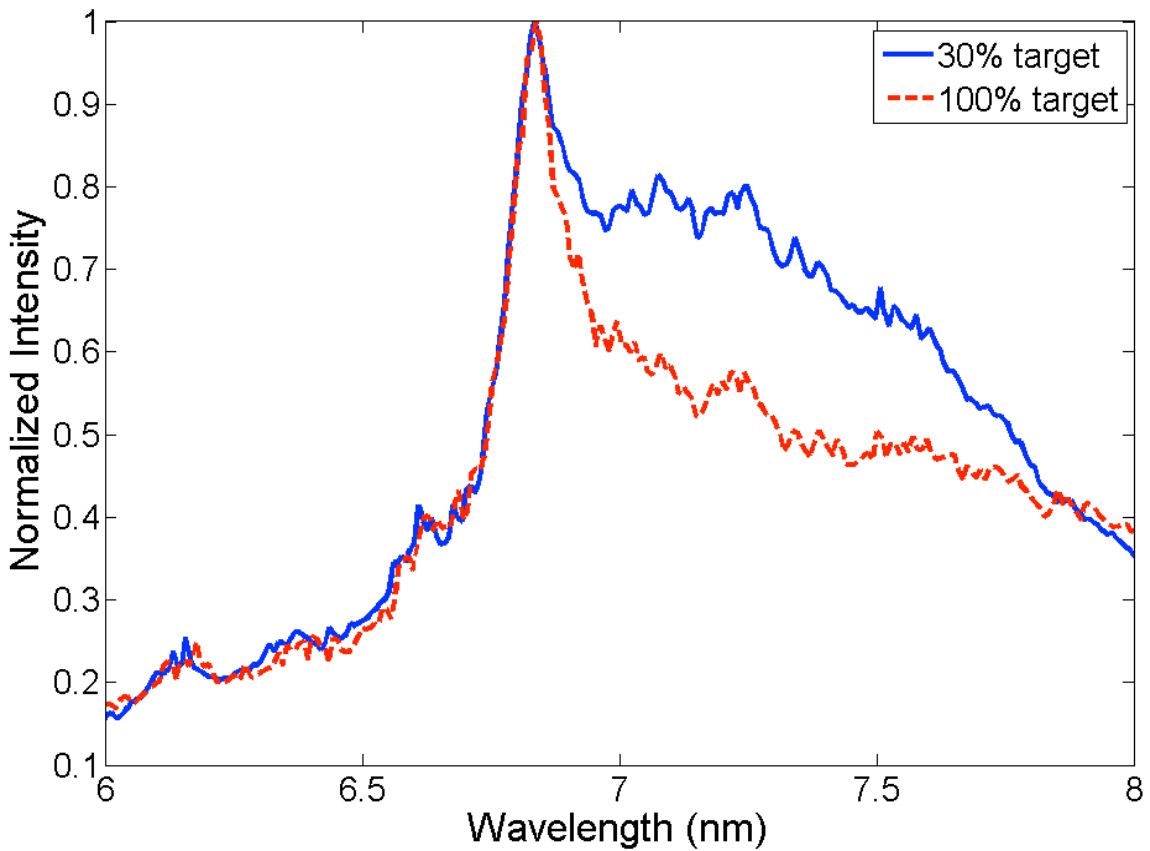


Fig 3: Emission spectra from low-density target at 30% Gd concentration (solid line) compared to 100% concentration for viewing angle (b) for a 10 ns laser pulse duration.

Cowan's suite of atomic structure codes [18] were used to calculate synthetic spectra for each relevant ion stage. The resulting spectra for each ion stage were then weighted by ion populations calculated within a collisional radiative model [19] and summed to give theoretical spectra for a given temperature. In Fig. 4 plots of theoretical spectra that best fit the leading and falling edges of that shown in Fig. 2(a) for the 150 ps laser pulse duration are presented. A plasma temperature of 60eV was found to give agreement for the short wavelength end of the spectrum while a lower temperature of 40eV was found to give best agreement to the long wavelength region. As the experimental spectra are time and space integrated it can be inferred that for the bulk of the emission, the plasma electron temperature varied between these two values. It was not possible to calculate an accurate fit for the spectra detected for the 10 ns laser pulse duration as to accurately model these spectra, both the effects of opacity and the full hydrodynamics describing the plasma expansion need to be included. In addition, as was the case with the development of Sn as a source of EUV emission at 13.5 nm, information on the photoabsorption cross sections for the low ion stages of Gd, found in the periphery of the plasma, need to be obtained to reliably model the spectra obtained in Fig. 2 for the 10 ns laser pulse duration [20].

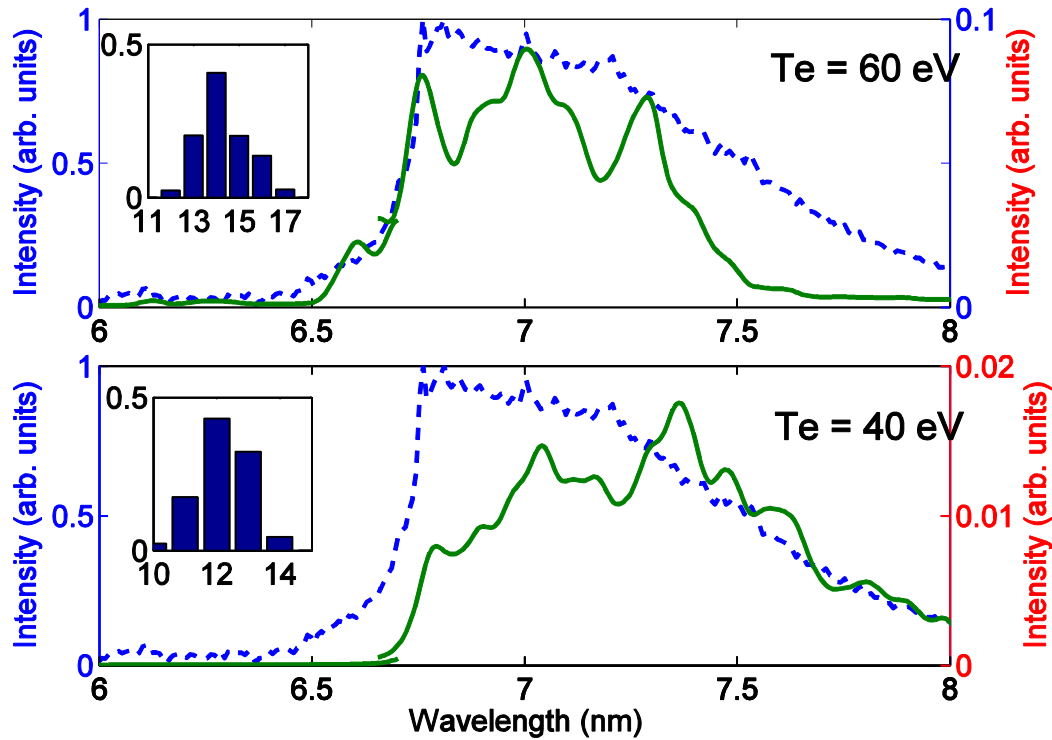


Fig 4: Theoretical spectra (blue, dashed line) that best fit the experimental spectrum shown in Fig. 2(a) for a 150 ps laser pulse duration (green, solid line). The inset shows a bar plot of the ion distribution at the electron temperature that gives the best fit.

In summary, we have demonstrated the effect of viewing angle on the spectral emission of a planar Gd target in the 6.7-nm spectral region for two target orientations with respect to the laser irradiation direction. We have shown a strong angular dependence of the detected emission spectra when produced with a 10 ns laser. We attribute this effect to absorption by low Gd ion stages and to anisotropic ion distributions. We have also shown that this effect is not as pronounced when the plasma is produced with a 150 ps laser resulting from the reduction in density of the EUV emitting region due to plasma expansion.

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