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# Optimizing conversion efficiency and reducing ion energy in a laser-produced Gd plasma

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## **Abstract**

We have demonstrated an efficient extreme ultraviolet (EUV) source at 6.7 nm by irradiating Gd targets with 0.8 and 1.06  $\mu\text{m}$  laser pulses of 140 fs to 10 ns duration. Maximum conversion efficiency of 0.4% was observed within a 0.6% bandwidth. A Faraday cup observed ion yield and time of flight signals for ions from plasmas generated by each laser. Ion kinetic energy was lower for shorter pulse durations, which yielded higher electron temperatures required for efficient EUV emission, due to higher laser intensity. Picosecond laser pulses were found to be the best suited to 6.7 nm EUV source generation.

In the last 18 months, the topic of beyond extreme ultraviolet (BEUV) light sources for future EUV lithography has become one of great interest. With the resolution of many of the problems involved with 13.5 nm tin (Sn) plasma sources [1], much research has already begun to shift towards shorter wavelength source development. Modeling work has proceeded on several high-Z materials [2,3], with gadolinium (Gd) laser produced plasmas (LPPs) becoming the focus of significant effort [4]. The choice of Gd arises from the fact that the same transition array that is responsible for emission at 13.5 nm in Sn plasmas lies in the reflection region of lanthanum boron carbide (La/B<sub>4</sub>C) multilayer mirrors, close to 6.7 nm. The same systematic investigations [5-8] are being carried out on 6.7 nm emission from Gd-based laser produced plasmas as were previously performed for Sn, with the impact of many different experimental parameters on the conversion efficiency (CE) of in-band emission under investigation.

In this work, processes involved in the laser-plasma interaction over varying laser pulse durations are investigated. Information on ion time of flight (TOF) signals was recorded to help better understand the effect of pulse duration on ion energy. The effects of pulse duration on CE and EUV generation from other source materials have been previously investigated [9-13]. For example, the maximum CE for neodymium doped yttrium-aluminium-garnet (Nd:YAG) laser irradiation of Sn targets was obtained using a 2.3 ns pulse by Ando *et al.* who showed that the optical depth increased with pulse duration [14]. The maximum CE observed for irradiation by carbon dioxide (CO<sub>2</sub>) lasers of Sn containing droplets, for the particular experimental conditions used in Ref [15], was for a pulse duration of 10 ns. By studying the effects of laser intensity on CE, the optimum laser intensity for irradiation of a given focal spot size can be defined. In general the flux required to maximize the CE

increases as the target radius decreases because of lateral expansion [16,17]. In the present work the laser intensity was varied from  $10^{11}$ – $10^{15}$  W/cm<sup>2</sup> to produce emission from Gd<sup>12+</sup> to Gd<sup>25+</sup>, whose resonant emission is around 6.7 nm [2,5,18-20]. To achieve efficient EUV emission and high CE, we focused on optimizing both the laser intensity and the laser pulse duration. The optimum electron temperature of a Gd plasma optimized for 6.7 nm emission is 3 times higher than that required to optimize a Sn plasma for 13.5 nm emission. The plasma expansion velocity is also larger as a result of this higher electron temperature, which, from theoretical modeling, has been calculated to be above 100 eV [2,21]. To limit the etendue, the plasma source size should be controlled by producing a small focal spot and shorter pulse duration in the LPP process. We therefore propose the use of a ps laser pulse to produce the required higher electron temperature, while keeping the source size small.

In this letter, we investigate the dependence of EUV emission and fast ion yield on laser intensity and pulse duration, to provide information essential for developing an efficient next generation lithography source. Peak laser intensities for maximum CE from nanosecond (ns), picosecond (ps) and femtosecond (fs) lasers were observed. Ion TOF signals for the LPPs produced by the ns, ps and fs pulses were also recorded.

Three lasers were employed in the experiments to achieve the desired variation of laser pulse duration and intensity, a 140 fs titanium:sapphire (Ti:sapphire) laser with an operating wavelength of  $\lambda = 800$  nm and maximum energy of 30 mJ, a 150 ps Nd:YAG with maximum output energy of 190 mJ at  $\lambda = 1064$  nm, and a 10 ns Nd:YAG with a maximum energy of 420 mJ at  $\lambda = 1064$  nm. Each laser beam was incident normally onto 100% planar Gd targets and after each laser shot the target surface was replenished. The in-band energy, into a 0.6%

bandwidth defined by currently available multilayer optics [22,23], was calculated using a calibrated EUV energy meter, in  $2\pi$  sr. The energy meter, consisting of a molybdenum boron carbide (Mo/B<sub>4</sub>C) mirror and a zirconium (Zr) filter, was oriented at 45° to the target normal. The output energy of each laser was changed to vary intensity while the focal spot diameter of each laser on target was fixed at 30–40 μm. TOF signals of the fast ions from the plasmas were recorded with a Faraday cup placed at 45° to the target normal at a distance of 10 cm with a bias of –17 V applied.

The influence of laser intensity on the CE, obtained by varying the output pulse energy, while maintaining constant spot size, is presented in Fig. 1. A maximum CE for the 150 ps pulses of 0.4% was observed compared to values of 0.3% and 0.12% for 10 ns and 140 fs laser irradiation, respectively. This compares to a 1.3% CE into a 2% bandwidth in the case of Sn LPPs. The optimum laser intensity for efficient 6.7 nm EUV emission was found to be close to  $7 \times 10^{13}$  W/cm<sup>2</sup>. For 10 ns pulses a peak CE close to  $4 \times 10^{12}$  W/cm<sup>2</sup> was observed. The drop in CE between these two laser intensity values may be ascribed to both pulse duration and plasma temperature effects. The latter influences the peak emission wavelength as described in Refs [2] and [5]. For 140 fs pulses the CE had a maximum of only around 0.12%, as the laser intensity was too high and plasma volume too small for efficient emission of photons around 6.7 nm. The optimum laser intensity to achieve the maximum CE was therefore observed with 150 ps laser pulses for operation at  $\lambda = 1.06$  μm. For a plasma in the collisional radiative regime, the electron temperature increases with increasing laser intensity [24]. The EUV emission, however, is not fully optimized due to strong self-absorption in the optically thick plasma that is created. From work on the same transitions in Sn plasmas, it was found that use of a target containing only 5% of the element produced a 50% increase in

the CE and that it occurred at a slightly higher flux, due to cooling by rapid expansion of the lighter ions present [25].

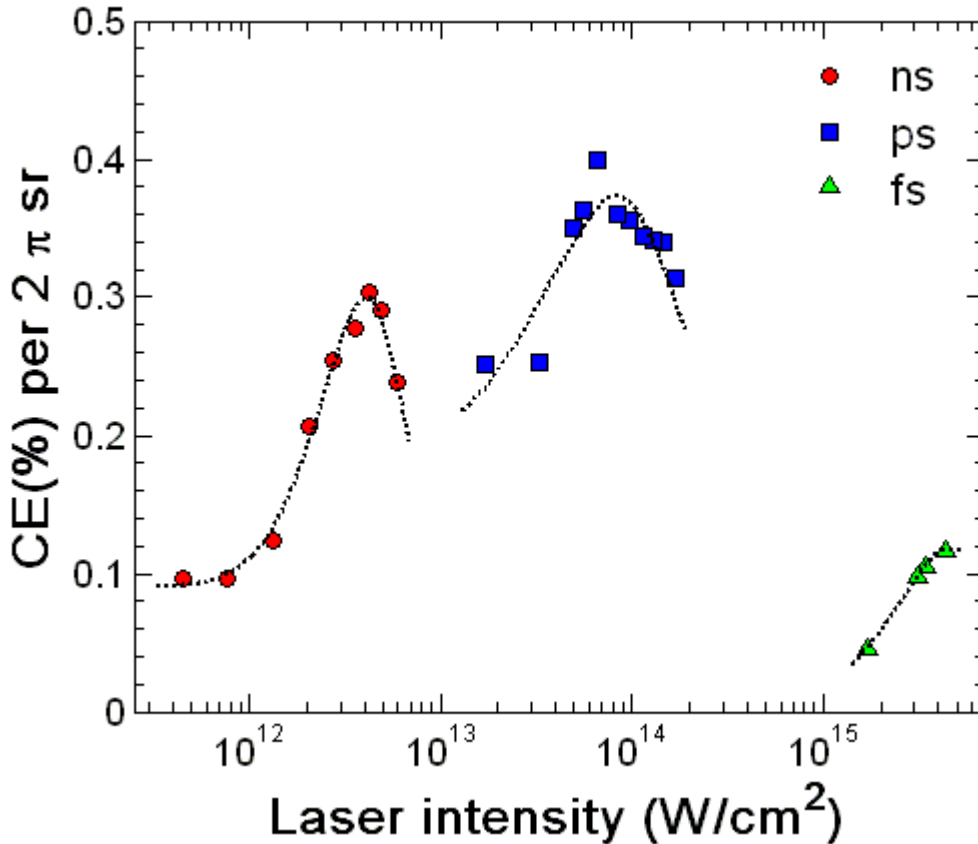


Fig 1: CE values recorded with EUV energy meter for ns, ps Nd:YAG and fs Ti:sapphire lasers as a function of laser intensity.

Figure 2(a) shows the electron temperature dependence on the laser intensity from a one-dimensional hydrodynamic code simulating the interaction of a laser at the wavelength of 1.06 μm with a high Z plasma. We evaluated the electron temperature at the peak intensity on the laser axis. According to the numerical simulation result, the electron temperature is of the order of 130 eV at a laser intensity ( $I_L$ ) of  $(6-8) \times 10^{13}$  W/cm<sup>2</sup> for a laser pulse duration of 150

ps. The electron temperature,  $T_e$ , in the high-Z plasma increased with increasing laser intensity as  $T_e \propto (I_L \lambda^2)^{0.4}$ , this is due to the large kinetic energy of the plasma hydrodynamic motion [15]. By use of a steady-state collisional radiative model [24] we calculated the Gd ion population as a function of the electron temperature at an electron density  $1 \times 10^{21} \text{ cm}^{-3}$ , which corresponds to the critical density for laser wavelength of  $1.06 \text{ }\mu\text{m}$ , as shown in Fig. 2(b). To produce the optimum ion population of  $\text{Gd}^{17+}$ – $\text{Gd}^{19+}$  the electron temperatures should be tuned between 80 to 130 eV. The CE was maximized at a laser intensity of  $7 \times 10^{13} \text{ W/cm}^2$ , which corresponds to an optimum electron temperature of 130 eV in Fig. 2(a).

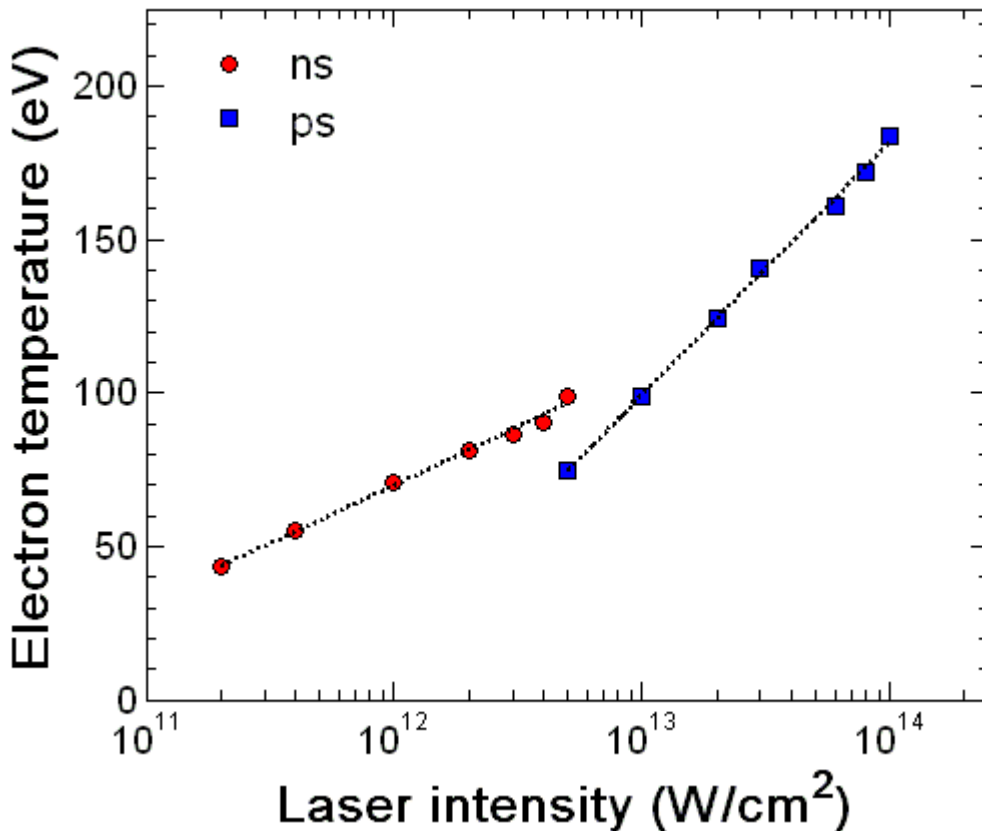


Fig 2 (a): Laser intensity dependence on the electron temperatures in high-Z plasmas

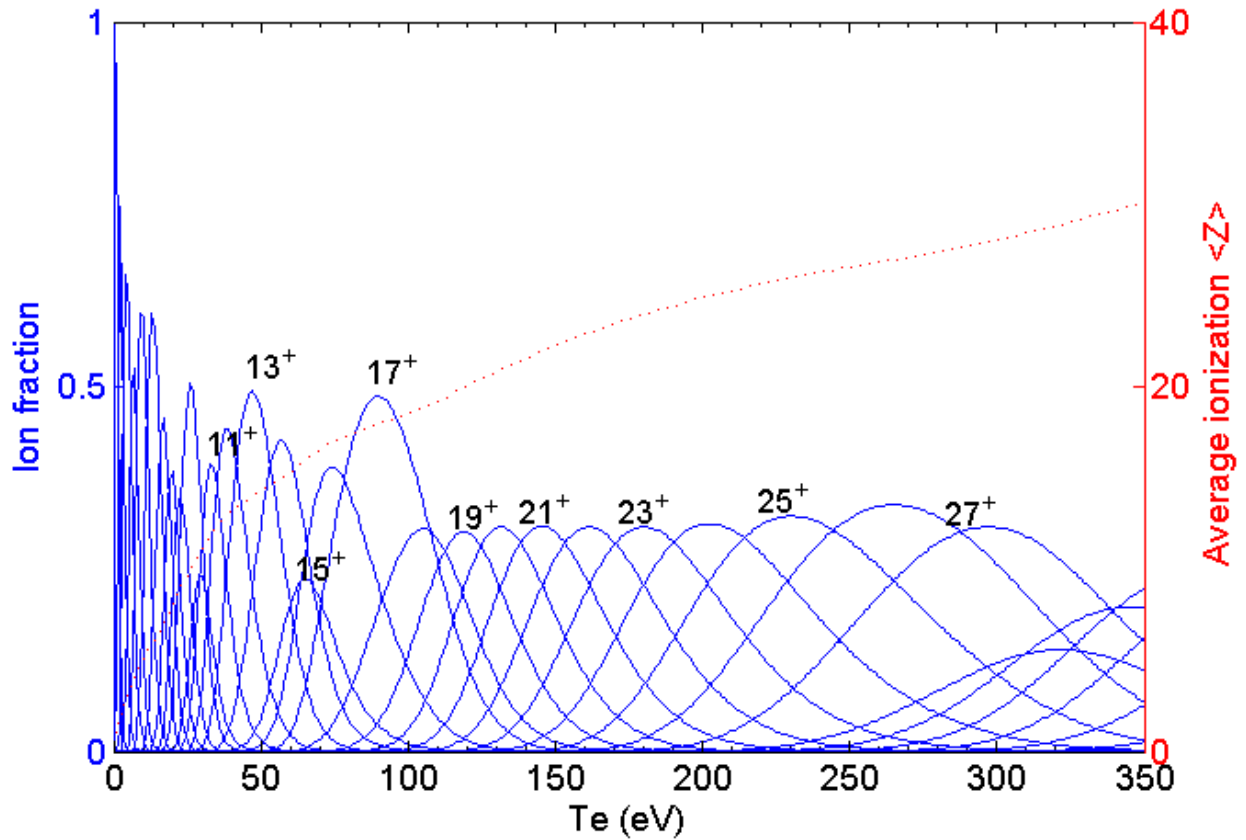


Fig 2 (b): The ion population of Gd as a function of the electron temperature.

This result is of great importance when it comes to realizing Gd LPPs as future BEUV sources for lithography. The ps laser irradiation showed an enhancement in CE and as we will demonstrate next, the shorter pulse duration also had a beneficial impact on the ion yield and TOF signals observed from the plasma.

Information on the ion yield and TOF are presented in Fig. 3. Typical flight signals recorded with the ns and ps pulses at three different laser power densities are shown in Figs. 3(a) and 3(b). The ion TOF at the laser intensity for optimum CE of the ps LPP was 9  $\mu$ s, compared to 2  $\mu$ s for the corresponding optimum intensity of the ns LPP. The time durations

of each TOF signal are lengthened by the continuous supply of material from the wide planar Gd target. The TOF signal duration would be shorter if a mass limited-target were used. The accelerating length, which originates from the plasma expansion, is present for a much shorter time in the 150 ps case. As a result, the ion yield at the time corresponding to the peak signal amplitude was seen to be lower for ps than ns Nd:YAG laser irradiation. The TOF as a function of laser intensity is presented in Fig. 4, which clearly shows longer flight times for ions from the fs and ps LPPs than the ns LPP. Due to the very short pulse duration of the fs laser, we observe a change in the trend for TOF as a function of laser intensity compared to the ns and ps LPPs. This is as a result of different ion acceleration processes beginning to dominate. The extremely short time scale of the fs plasma lifetime means hydrodynamic motion is suppressed, due to the fs pulse duration being shorter than the electron-phonon relaxation time [26] and hence charge separation dominates. There are three methods available to reduce the maximum ion kinetic energy [27]: (I) Use of low-density targets. This has been investigated using 30% Gd targets [8], and has the added bonus of giving an increase in CE by suppression of self-absorption effects. (II) A lower electron temperature. This, however, is not viable as the temperature requirement for reaching ion stages from  $Gd^{12+}$  to  $Gd^{25+}$  is greater than 100 eV [2]. (III) Use of shorter pulse duration lasers to irradiate the target surface. It is known that shorter pulse duration will form a small plasma, as the size is determined by the lifetime of the laser pulse. The electrostatic field induced by the formation of the plasma determines the TOF and maximum kinetic energy of ions produced [27]. The smaller electrostatic potential as created by the fs and ps lasers results in longer TOF and a reduction in the peak ion kinetic energy. In the near future, the charge-separated ionic distribution will be measured by use of an electrostatic analyzer.

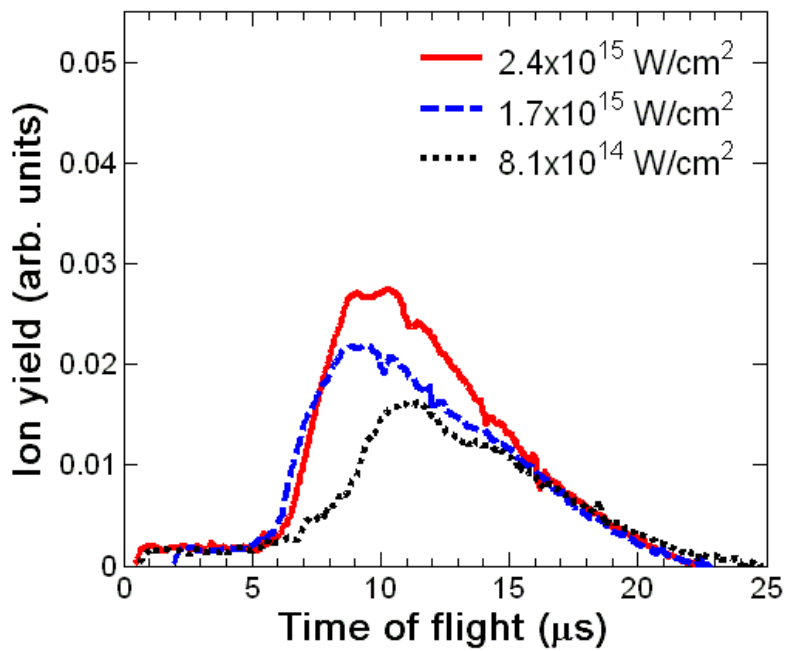
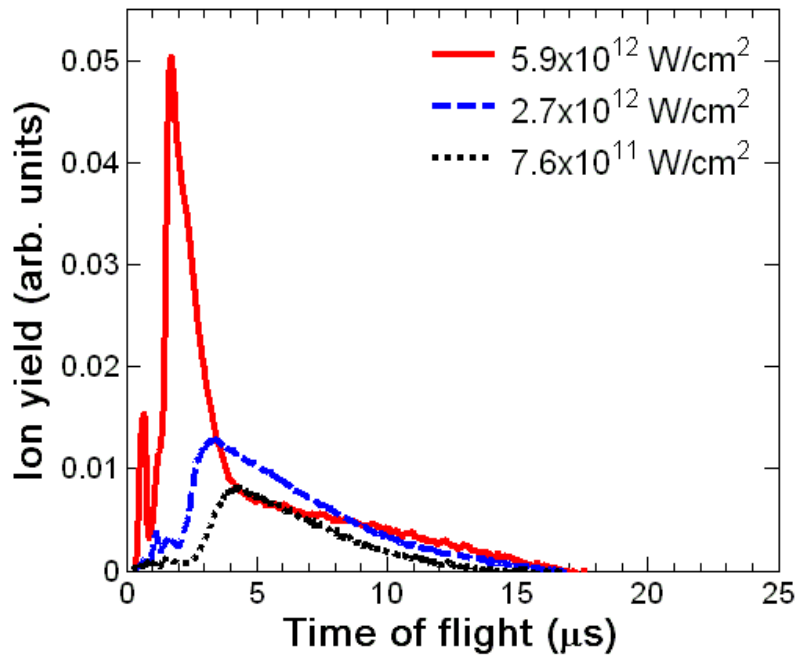


Fig 3: Time of flight signals recorded for ions emitted by plasmas formed with laser pulse durations of 10 ns (a) and 150 ps (b) at three laser intensity values.

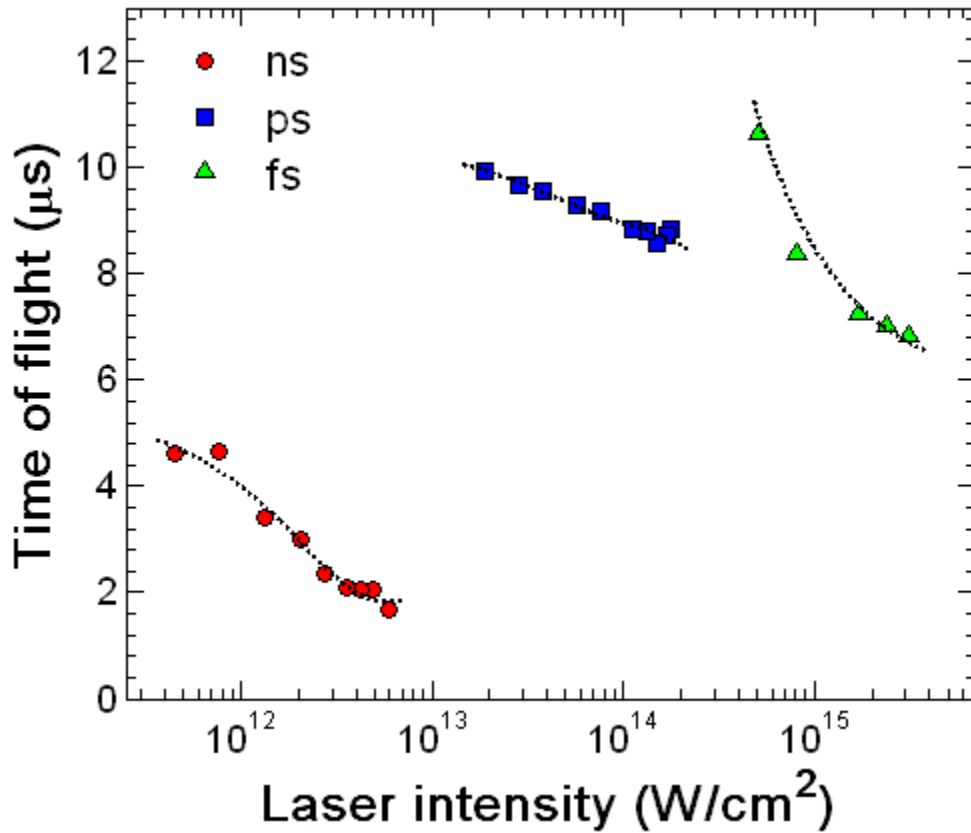


Fig 4: TOF signals observed for plasmas produced with ns and ps Nd:YAG lasers, and the fs Ti:Sapphire laser as a function of laser intensity.

In summary, we have demonstrated an increased CE using high intensity 150 ps Nd:YAG laser pulses as compared with ns and fs pulses. The shorter pulse duration also has the effect of increasing ion TOF and reducing peak kinetic energy. These results point towards the use of shorter pulse duration and higher intensity carbon-dioxide (CO<sub>2</sub>) lasers to obtain higher EUV emission energy. The emission would not only increase due to the reduction in opacity due to the reduction in plasma critical density with the use of longer laser

wavelength ( $\lambda = 10.6 \mu\text{m}$ ), but the plasmas would also produce ions with lower kinetic energy, which would assist with debris mitigation and reduce the damage to optical components by fast ion bombardment. Thus work is needed on CO<sub>2</sub> laser development to guide ps laser development to support high volume manufacturing requirements.

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