Optimum Pre-pulsing and Target Geometry of LPP for Efficient EUV and BEUV Sources

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ABSTRACT

Light sources for extreme ultraviolet Lithography (EUVL) are continued to face challenges in the demanding performance for high volume manufacture. Currently EUV and beyond EUV (BEUV) community are focused on the dual-pulse laser produced plasma (LPP) using droplets of mass-limited targets. These systems require extensive optimization to enhance the conversion efficiency (CE) and increase components lifetime that requires significant experimental and development efforts.

We continued to enhance our comprehensive HEIGHTS simulation package and upgrade our CMUXE laboratories to study and optimize LPP sources and to make projections and realistic predictions of near future powerful devices. HEIGHTS package includes 3-D detail description of all physical processes involved in LPP devices. The models continued to be well benchmarked in each interaction physics phase of plasma evolution and EUV/BEUV production as well as in the integrated LPP systems. We simulated LPP sources in full 3-D geometry using Sn and Gd droplets and fragmented targets composed of microdroplets as a result of prepulse or from mist of tiny droplets distribution. We studied mass dependence, laser parameters effects, atomic and ionic debris generation, and optimization of EUV/BEUV radiation output, the requirements for mitigating systems to reduce debris effects. Our enhanced modeling and simulation include all phases of laser target evolution: from laser/droplet interaction, energy deposition, target vaporization and fragmentation, ionization, plasma hydrodynamic expansion, thermal and radiation energy redistribution, and EUV/BEUV photons collection as well as detail mapping of photons source location and size. Modeling results were benchmarked against experimental studies for the in-band photons production and for debris and ions generation.

Keywords: LPP, CE, EUV, BEUV, HEIGHTS, mass-limited targets, debris mitigation

1. INTRODUCTION

Dual-beam lasers interacting with small tin droplets are currently the most efficient systems for producing of 13.5 nm photon source. The concept of the pre-pulse technique was initially applied for the optimization of extreme ultraviolet (EUV) sources produced from water droplets [1]. Later, experiments and modeling of dual-beam lasers with two wavelengths, fundamental wavelength of Nd:YAG for the prepulse and CO_2 for the main pulse, showed significant increase in the CE from tin droplets [2]. Further analysis and optimization of laser parameters for the prepulse, the delay time between pulses, in combination with droplet size, showed another way of efficient target preparation to enhance the conversion efficiency (CE). This also includes, for example, applying the fourth harmonic of Nd:YAG laser as the most suitable laser for the initial, pre-pulse stage [3]-[5]. Lower laser reflection from the solid tin and higher plasma critical density for laser with 266 nm wavelength facilitated the entire evaporation of small, 10 - 20 µm, droplets [5]. This can be achieved at relatively low laser intensities, around $2x10^{10}$ W/cm^2, that leads to low particles velocities in the developed plumes and more homogenous expansion of plasma/vapor cloud. Recent experiments with various materials showed large difference in the ablation rate between the 266 nm and 1064 nm lasers. For example, approximately ten times more of silicon and tin can be ablated by 266 nm laser in the case of planar targets [6],[7]. The evaporation rate of droplets can be even higher due to motion of the developed plasma around the droplet surface that prevents formation of an efficient shielding layer above the target.

Near complete evaporation of small droplets permitted efficient absorption of the main laser photons. The expanded cloud of a relatively homogeneous mist allowed using beams with large spot sizes that significantly increased the CE of LPP devices. Furthermore, the dependence of the CE for different droplet sizes was predicted based on optimization of laser interactions with the evaporated and expanded target [5],[8]. These dependencies and limitations for laser pulse durations were explained by hydrodynamics effects.

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In the present work, we studied and compared the analysis and optimization of the main laser pulse with shorter wavelengths, i.e., specifically we investigated the potential use of Nd:YAG laser for both pre-pulse and main pulse stage and compared the efficiency of such devices with the efficiency of the current Nd:YAG / CO_2 combination system.

We also continued our analysis of the 6.x nm Gd sources and compared the dependence of EUV and BEUV sources efficiency and resulting plasma debris/ions concentration.

2. COMPARISON OF Nd:YAG / CO_2 and Nd:YAG / Nd:YAG DUAL-BEAM SYSTEMS

Our previous analysis showed that laser with 266 nm wavelength and small energy, i.e., around 1.5 mJ, can evaporate about 80% of a 30-µm Sn droplet [4]. Optimization of CO_2 laser spot size and varying delay after pre-pulse allowed increasing the CE of the source by 6 times in comparison with the CE produced from a single CO_2 laser of the same droplet. HEIGHTS simulation also showed that the number densities in the expanded plume should be at least of the order of 10^{17} cm^{-3} for the efficient absorption of laser photons with 10-µm wavelength. The optimum delay after the pre-pulse is corresponded with the development of large volume with above number densities that allowed using large spot size as well as increased the area of efficient laser/matter interactions in axial direction. For example, the optimum delay for CO_2 laser with 300-µm spot size was around 400 - 500 nanoseconds.

We studied the potential of application of Nd:YAG laser as the second main stage in the dual-beam systems. Figure 1 shows that the combination of two Nd:YAG beams allows two times increase in the CE in comparison with single Nd:YAG laser device. Efficient source using this configuration can be produced in the more narrow range of delay times between pulses. The CE of sources produced at earlier times, around 50 ns after pre-pulse, and later, after 250 ns was significantly reduced and was even lower than the CE produced by the single laser.

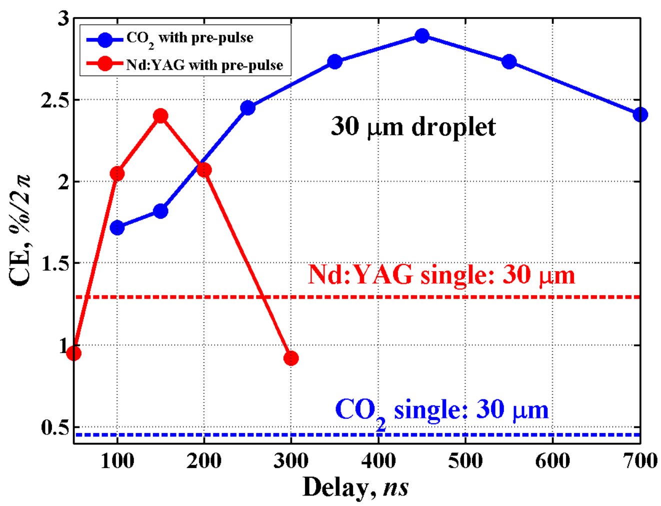
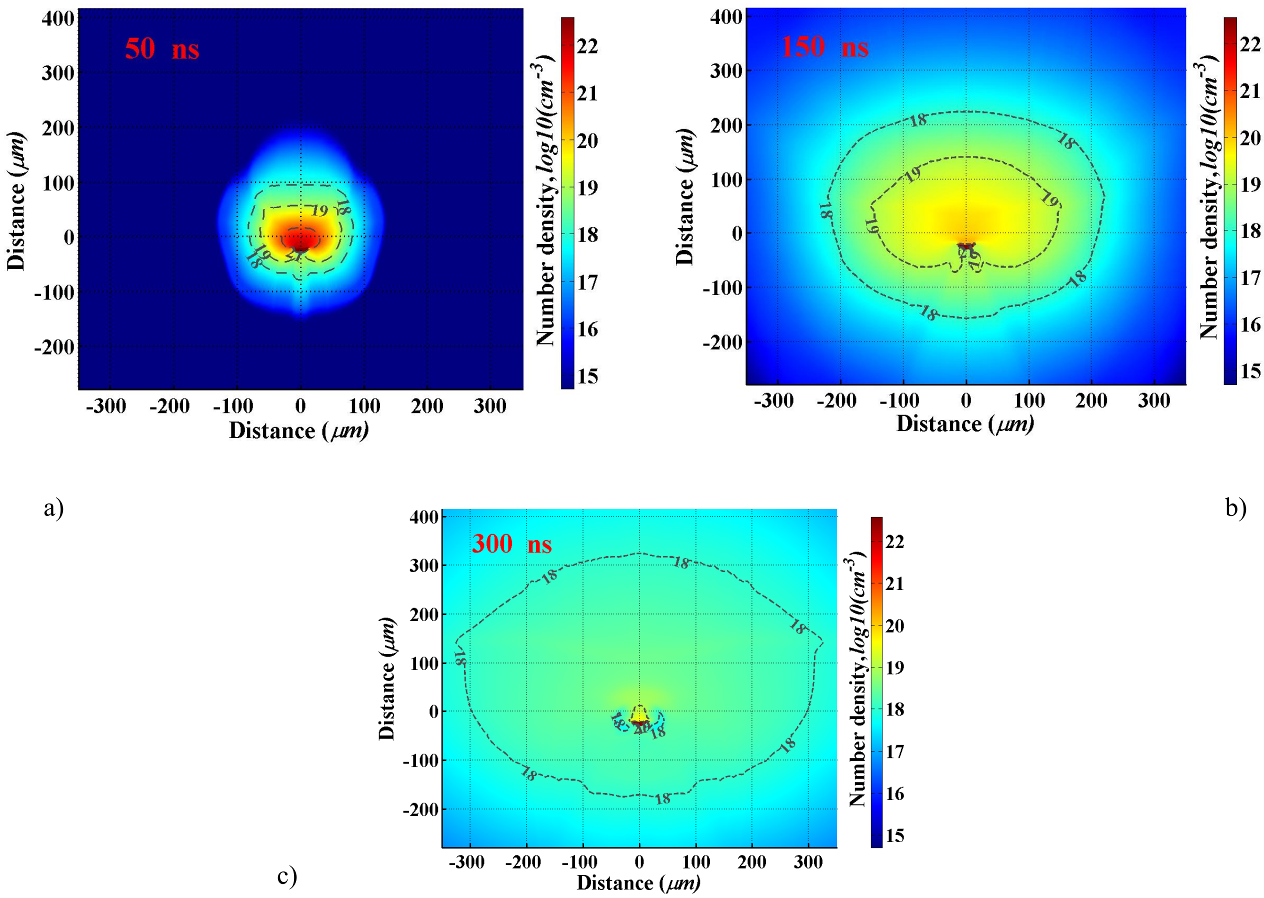


Figure 1. Difference in optimization of Nd:YAG / Nd:YAG and Nd:YAG / CO_2 dual-beam devices. Laser parameters for the main pulse: Nd:YAG with 7.5x10^{10} W/cm^2 intensity, 10 ns pulse duration and 200 µm spot; CO_2 with 7.5x10^9 W/cm^2 intensity, 30 ns duration and 300 µm spot

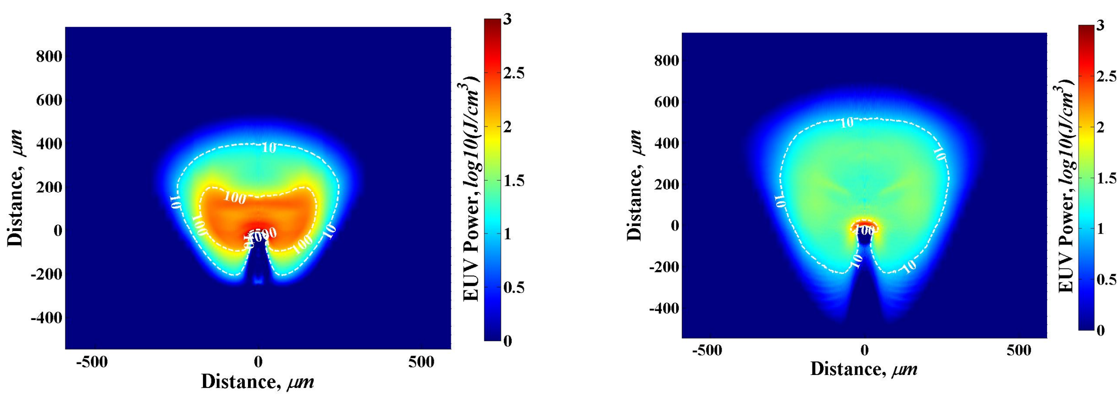
Comparative analysis of number densities at different times after pre-pulse (Fig. 2 a, b, and c) and matching of 200 µm laser spot to spatial distribution of density show that number density in the developed plasma/vapor plume should be of the order of 10^{19} cm^{-3} for the efficient absorption of 1 µm laser photons. Lower peripheral densities at earlier times and lower densities in the entire plume at later time results in significant loss of laser photons, which are transmitted through the media without much interaction. About 70% of the main laser photons was not used in the case of both delays in contrast to efficient interactions at 150 ns after pre-pulse when more than 90% of laser energy was absorbed in the plume. Thus, number densities for the efficient absorption of photons with 10 µm and 1 µm wavelengths differ substantially by two orders of magnitude that is related to the main dependences in the inverse bremsstrahlung such as quadratic dependence on ions density and laser wavelength.



a) b) c)

Figure 2. Snapshots of number densities distribution in vapor/plasma plume created from 30 μm droplet by pre-pulse laser with 266 nm wavelength at different times after pre-pulse: a) 50 ns; b) 150 ns and c) 300 ns

The Nd:YAG dual laser system, with the parameters studied, produces less efficient source in comparison with CO_2 laser beam being the main pulse, however the source is more intense and brighter. Due to the two orders of magnitude difference in plasma critical densities between the two lasers, more dense plasma is created by Nd:YAG laser in the plume that results in more intense EUV photons radiation.



a) b)

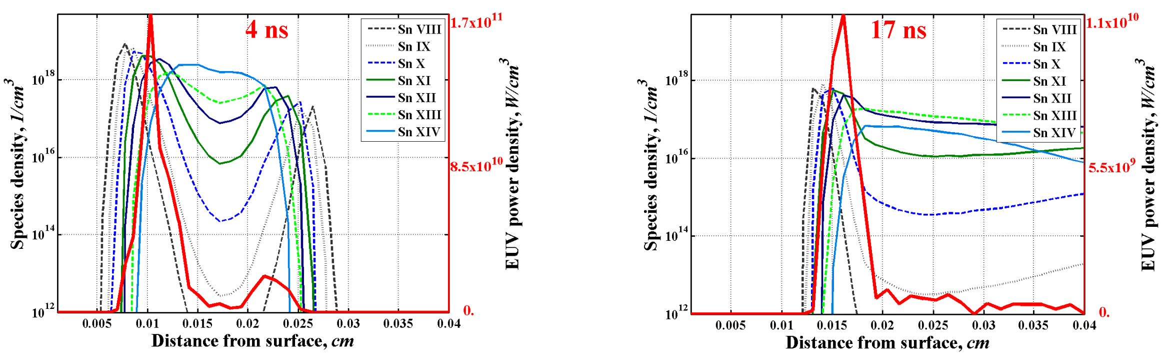
Figure 3. EUV sources created in vapor/plasma plumes by a) Nd:YAG and b) CO_2 lasers

Figure 3 (a and b) shows the difference in EUV source size and strengths between these two lasers systems. The EUV source in both cases is created in the compressed layers developed by laser energy in vapor/plasma plume and the source is moved toward the target during the pulse in opposite to dynamics of source created by single laser from a solid target.

Currently, the use of the CO_2 laser for the main pulse in dual beam system is more pursued for better source optimization and efficiency enhancement. However, the anticipated higher stability of Nd:YAG lasers and the more accurate spatial alignment/spot size and temporal profile can promote this dual-beam laser systems. Therefore, comparative analysis and further optimization of various combinations of laser wavelengths supported by detailed and accurate computer simulations need to be performed to design the most cost-efficient EUV source.

3. DEPENDENCE OF SOURCE SIZE AND LOCATION ON IONS DISTRIBUTION

Analysis of tin ions distribution provides clear picture of source dependence on plasma characteristics. Figure 4 a) and b) shows the spatial distribution of Sn^{8+} - Sn^{14+} ions which can produce 13.5 nm photon radiation. The data shown for the EUV source (red plot), developed along laser beam at the spot center, correspond to source of photons collectable in 2π sr, i.e., taking into account part of photons that was absorbed on their way to the collecting optics.



a) b)

Figure 4. Spatial distribution of Sn ion species and corresponding EUV sources created in vapor/plasma plumes by a) Nd:YAG and b) CO_2 lasers

Two peaks can be seen of EUV power density along laser axis (Fig. 4a) that correspond to two areas with ~30 eV plasma temperatures (Fig. 5) with highest concentration of contributing ions. The difference in total ions number in these two peaks determine the difference in source intensity which is one order of magnitude higher in the area located closer to the target. Part of EUV photons emitted from this area was absorbed in upper layers. However, higher temperature and lower plasma density in the area between two sources leads to prevailing ion species with higher charges which do not affect emission/reabsorption of 13.5 nm photons. Therefore, due to lower concentration of absorbing ions in the region with maximum temperatures as well as much lower density of these ions in the second area of the source, the absorption of photons emitted from the first source is significantly lowered.

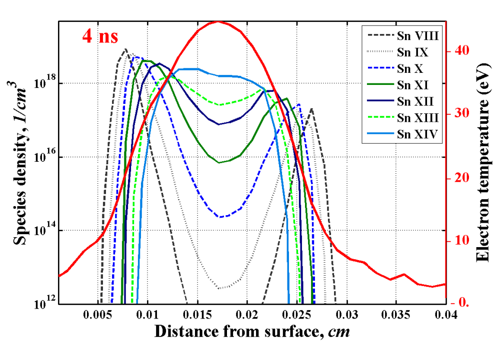


Figure 5. Electron temperature and Sn ion species concentration developed by Nd:YAG laser in vapor/plasma plume

The concentration of producing ions in the source created by CO_2 laser is comparable with concentration in the area of the second source in Nd:YAG produced plasma, i.e., the intensities of these sources are also similar. There is no significant second EUV source in CO_2 produced plasma due to the overall low densities in such plasma.

Strong dependence of desired photon source on electron temperature is less pronounced for beyond EUV (BEUV) radiation sources from Gd where photons are produced at wide range of plasma temperatures (Fig. 6). Detailed analysis of ions population in Gd plasma and comparison of 6.75 nm photon source location with plasma species concentration (Fig. 7) show high reabsorption of BEUV photons in the area with high concentration of ions producing BEUV photons. It is also shown that the area with low ions concentration, above the main source, produces comparable BEUV radiation due to the significantly reduced reabsorbing effect.

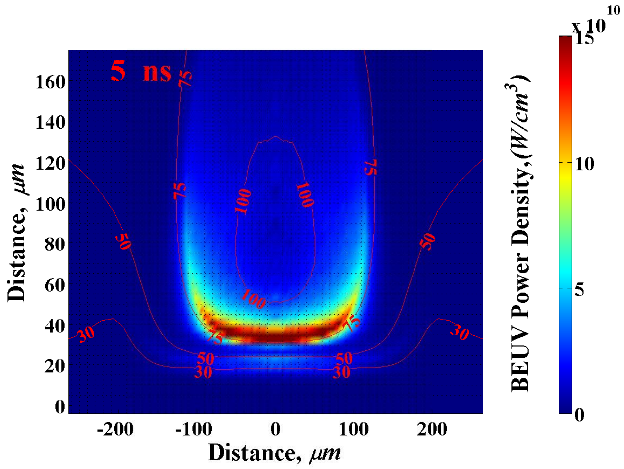


Figure 6. Source of 6.75 nm photons and electron temperatures distribution (red contour) in Gd plasma created by Nd:YAG laser with $5x10^{11}$ W/cm^2 intensity and 200 μm spot

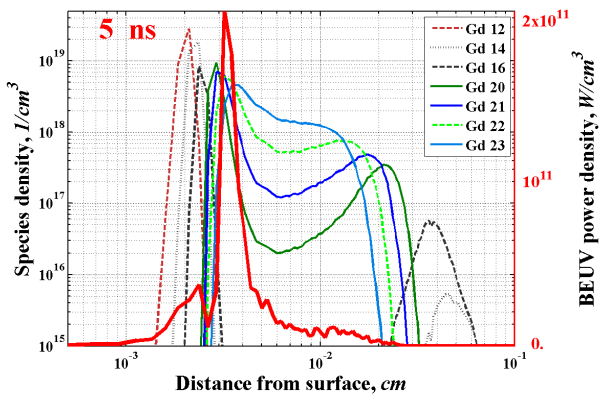


Figure 7. Spatial distribution of Gd ion species and corresponding source of 6.75 nm photons in Gd plasma

4. EFFECT OF BACKGROUND PRESSURE ON SOURCE EFFICIENCY

Processes of hydrodynamic plasma expansion and confinement by laser can produce various effects influencing the EUV efficiency of the source, particularly in high-frequency source operation.

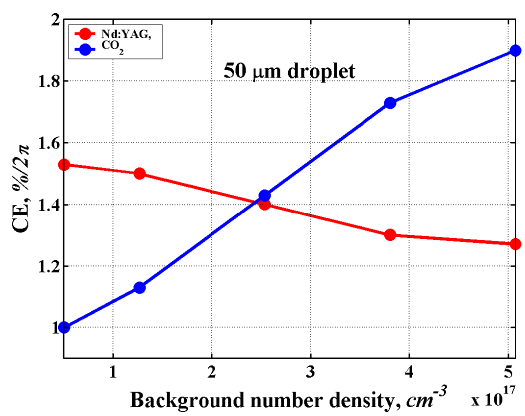


Figure 8. CE of EUV source produced from Sn droplet at various chamber conditions

For example, our HEIGHTS simulations showed that artificially applying background vapor around the droplet, the efficiency of EUV source produced by single CO_2 laser can be significantly increased. This situation can resemble the conditions when droplets will be delivered to the laser spot area during high repetition source rate and/or the mist produced during previous laser/droplet interactions that can result in higher background pressure in the chamber. Figure 8 shows that the efficiency of the source produced by CO_2 laser could be two times higher in the presence of surrounding vapor, while the CE of similar system with Nd:YAG laser is reduced in comparison with vacuum conditions.

Increase in the efficiency of CO_2 device is related to the development of compressed plasma layer in surrounding vapor (Fig. 9) with optimum temperatures for EUV emission. Electron temperatures in the outer compressed layer reach 25-30 eV that leads to producing EUV photons which can reach collecting surfaces without losses due to low electron densities in surrounding plasma and, therefore, low absorption of EUV radiation. The created source at these conditions has low intensity. However, the relatively large volume of this source can significantly affect the overall efficiency of the system (Fig. 10).

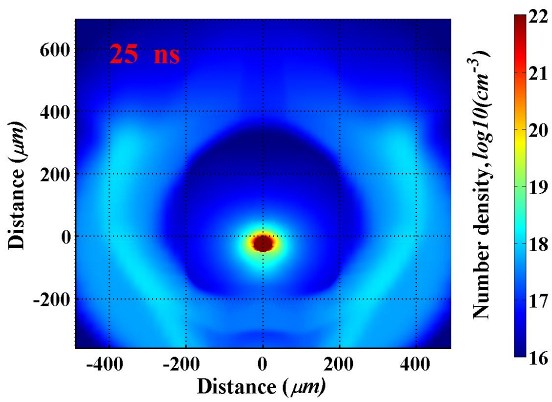


Figure 9. Number density distribution in compressed layer

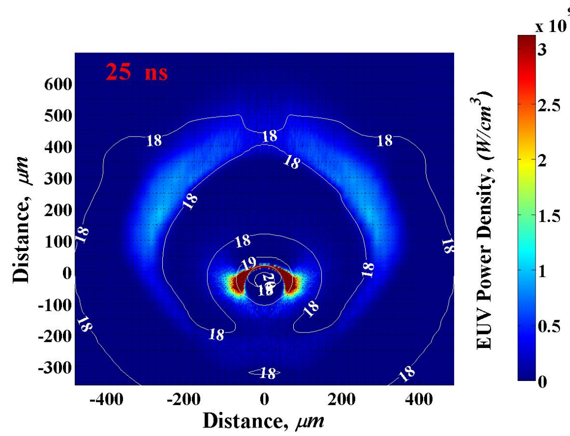


Figure 10. EUV source from evaporated material around the droplet and from compressed plasma layer formed from background vapor

5. CONCLUSION

Requirements of high volume manufacture to develop cost-efficient and high power EUVL system promote further investigation of possible ways of source improvement. We integrated state-of-the art fundamental and detailed models of atomic and plasma physics and hydrodynamics processes in our HEIGHTS full 3D package for accurate calculations of EUV photons productions and collections and ways to enhance source efficiency. Our analysis showed that first harmonic of Nd:YAG laser can also be used as the main pulse in dual-beam systems. While the efficiency of Nd:YAG / Nd:YAG devices is lower in comparison with Nd:YAG / CO_2 combination, produced source could be brighter and has smaller size that can be favorable due to the requirements needed for the optical collecting system. We also found that the residual background vapor that may exist in high-frequency operation, surrounding small droplets, can lead to more efficient sources produced using CO_2 laser. Similar environment in Nd:YAG devices could lead to a reduced source efficiency in comparison with vacuum conditions.

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