Photopumping of XUV Lasers by XFEL Radiation

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Within the next year the XUV Free-Electron Laser (XFEL) now under construction at DESY is expected to generate highly collimated XUV pulses with 10^{13} photons and a duration of 100 fs. Focusing this radiation to a spot some 10 μm in diameter generates intensities of up to 10^{16} W/cm^2. Such pump intensities make the investigation of photo-pumped XUV lasers feasible. We present simulations taking into account two different mechanisms generating the gain: 1. Photoionization with subsequent three-body recombination which takes advantage of the monochromaticity of the pump radiation to generate cold electrons [1]; 2. innershell ionization in which transient inversion is obtained by generating a hole in an otherwise completely filled shell [2]. The simulations show that under appropriate conditions both mechanisms generate high gain [3]. However, further issues must be considered, such as propagation of the pump pulse in the medium to be pumped.

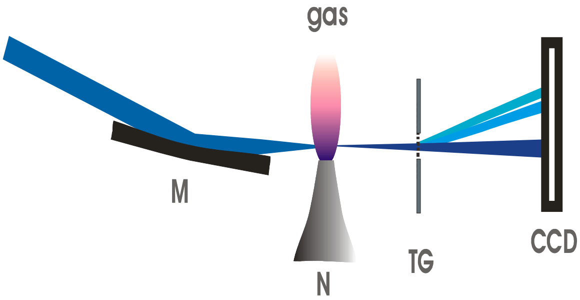

Fig. 1: Layout of the experiment. M: mirror; N: nozzle; TG: transmission grating.

A layout of the proposed experiment is shown in fig. 1. The XFEL pump source is weakly focused by a grazing-incidence elliptical mirror into a helium gas puff. The generated radiation is dispersed in a transmission grating spectrometer (to separate it from the pump radiation) and detected with a soft X-ray CCD. The simulations calculate the electron temperature T_e resulting from photoionization and collisional and radiative processes, with the main contribution being due to three-body recombination. The time-dependent occupation of the levels is calculated by means of a collisional radiative code.

1. XUV lasers in He I and He II

The He I laser uses 25 eV pump photons (just above the ionization potential of 24.6 eV) to generate gain on the He-α transition at 58.4 nm. The temporal evolution of the gain is shown in fig. 2 for different densities N_0. The shape of the pump pulse is also included. Gains of the order of 100 cm^{-1} are generated.

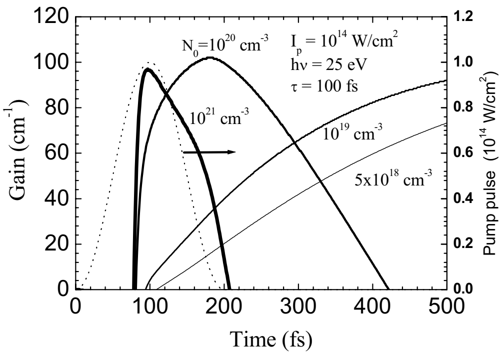

Fig. 2: Temporal evolution of He I laser gain for different densities. The pump pulse is shown dotted.

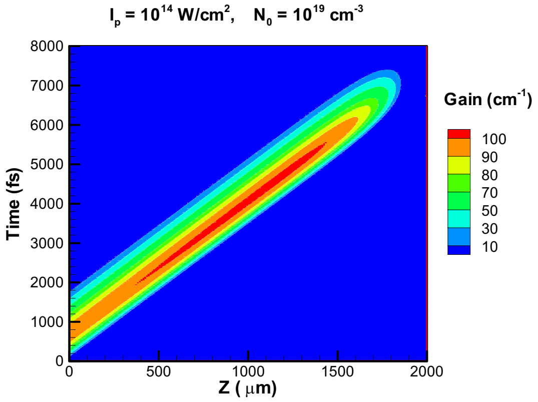

Fig. 3: Contour plot of the gain coefficient of the He I laser.

To attain a high gain length product the pump pulse must propagate through the medium for a sufficiently long distance. Saturation requires $gL > 15$. In fig. 3 we show a contour plot of the gain for a helium density of 10^{19} cm^{-3} at a pump intensity of 10^{14} W/cm^2. In spite of a high absorption coefficient the pump propagates a distance of almost 2 mm into the medium. This can be understood by realizing that the helium ground state is strongly depleted. A gain length product >15 is achieved under this condition.

The He II laser operates on the Lyman-α transition of hydrogenic helium with a wavelength of 30.4 nm. In fig. 4 the time-dependent gain coefficient for the He II Lyman-α transition at different densities is displayed. The pump intensity is 10^{15} W/cm^2, a factor of 10 higher than that used for He I. Here the gain only slowly rises for 10^{19} cm^{-3} and does not reach a high value. This is due to inefficient ionization of helium gas by the 55 eV photon. At higher densities the gain again reaches very high values. The simulations exhibit an intensity window for the gain, i.e. too low an intensity generates only low gain, but an intensity which is too high also results in small gain. This result can be understood by realizing that high intensity leads to high electron temperature by inverse bremsstrahlung heating. The gain is further reduced by ionization from the upper laser level.

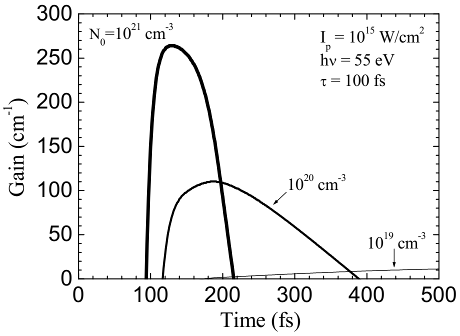

Fig. 4: Temporal evolution of He II gain for different electron densities.

2. Li II innershell laser

We present simulation results for the case of an innershell laser [2] pumped by an XFEL. Interest in innershell lasers derives from the fact that the states forming the upper laser level are already occupied and, thus, very high gain should be generated. In general, innershell lasers suffer from a high rate of loss of inversion due to the Auger effect. However, the problem of the Auger transition is not pertinent if the atom contains only a single outer electron, as in Li and Na. Ionization of a 1s electron of neutral lithium generates gain at the He-α line of Li II with a wavelength of 19.9 nm. However, transfer of the 2s electron of the neutral to the 2p level is required. This is possible by means of a visible laser tuned to the 2s – 2p resonance line of atomic lithium at $\lambda = 671$ nm. Figure 5 shows the result of a simulation of the gain on the He-α line of Li II for a pump intensity of 10^{14} W/cm^2, a pump photon energy of 68 eV and at densities ranging from 10^{18} to 10^{21} cm^{-3}.

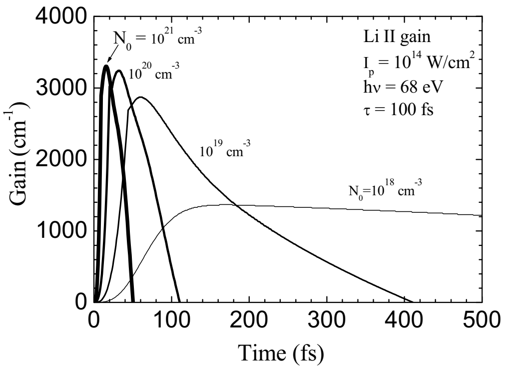

Fig. 5: Time-dependent gain of Li II laser.

The figure shows that very high gain is indeed generated at 19.9 nm. The duration of the gain is limited by collisional ionization of the electron in the n = 2 level. At 10^{20} cm^{-3} the gain duration is 60 fs and at the (somewhat hypothetical) density of 10^{21} cm^{-3} the gain lasts only for 30 fs. These conditions would thus lead to considerable shortening of the laser pulse compared with the pump pulse, a feature most welcome for many experiments.

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[2] M. A. Duguay and P. M. Rentzepis, Appl. Phys. Lett. **10**, 350 (1967).

[3] K. Lan, E. E. Fill, and J. Meyer-ter-Vehn, Europhys. Lett. **64**, 454 (2003).