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Photo-ionized neon plasmas induced by radiation pulses of a laser-plasma EUV source and a free electron laser FLASH

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Abstract

In this work, a laser-produced plasma extreme ultraviolet source and a free electron laser were used to create Ne photo-ionized plasmas. In both cases, a radiation beam was focused onto a gas stream injected into a vacuum chamber synchronously with the radiation pulse. Extreme ultraviolet radiation from the plasma spanned a wide spectral range with pronounced maximum centered at $\lambda = 11 \pm 1$ nm while the free electron laser pulses were emitted at a wavelength of 32 nm. The power density of the focused plasma radiation was approximately 2×10^7 W/cm^2 and was seven orders of magnitude lower compared with the focused free electron laser beam. Radiation fluences in both experimental conditions were comparable. Despite quite different spectral characteristics and extremely different power densities, emission spectra of both photo-ionized plasmas consist of the same spectral lines within a wavelength range of 20 to 50 nm, however, with different relative intensities of the corresponding lines. The dominating spectral lines originated from singly charged ions (Ne II); however, Ne III lines were also detected. Additionally, computer simulations of the emission spectra, obtained for photo-ionized plasmas, driven by the plasma extreme ultraviolet source, were performed. The corresponding measured and calculated spectra are presented. An electron temperature and ionic composition were estimated. Differences between the experimental spectra, obtained for both irradiation conditions, were analyzed. The differences were attributed mainly to different energies of driving photons.

Keywords: Extreme ultraviolet; Free electron laser; Laser plasma; Photo-ionization

INTRODUCTION

Interaction of high intensity, nanosecond laser pulses with gaseous media may result in formation of plasmas with relatively high temperature on the order of several tens or even hundreds of electron-volts. High intensity of the laser pulse is required to overcome a threshold for an optical breakdown. The problem is that the ionization potential of atoms or molecules exceeds the energy of a single photon several times, even in case of ultraviolet lasers. It means that for laser beams with too low intensity plasma cannot be created. In case of high intensity laser beam, multiphoton ionization becomes possible and some number of free electrons appears. These electrons are accelerated in the strong optical field, initiating an avalanche of ionization. Further collisional ionization and excitation leads to formation of a laser spark and conversion of the laser energy into plasma thermal energy, due to inverse bremsstrahlung. Temperature of the plasma formed this way is relatively high because of high power density in the interaction region exceeding 10^{11} W/cm^2. High plasma temperature results in multiple ionization and intense emission in extreme ultraviolet (EUV) or soft X-ray wavelength range.

Quite different plasmas are formed in case of irradiation of any gas with a beam of high energy photons with energies exceeding several times the ionization potential. These photons not only ionize atoms or even the resulting ions, but also produce electrons with energies sufficient for further ionization or excitation. There is no intensity threshold to be overcome for ionization, thus even photon beams with intensities of several orders of magnitude lower comparing to the laser

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beam, can produce plasmas. Because of low power density required, electron temperature of such plasmas can be much lower comparing to laser plasmas produced in gases, even below 1 eV. Apart from that, depending on the irradiation time, gas density and size of the ionized region, parameters of the photo-ionized plasmas can be far from thermodynamic equilibrium. As a result, energies of the emitted photons are usually much higher than in case of local thermodynamic equilibrium plasmas with the same electron temperature.

Photo-ionized plasmas are common in Space. Spectral investigations of these plasmas can provide information about different astrophysical objects emitting X-ray radiation that irradiate surrounding gases. Interpretation of the observed spectra requires constructing of physical models and performing laboratory experiments that support the accuracy of the models. Some experiments concerning laboratory simulations of the photo-ionized plasmas created in accretion discs were performed in high-energy density (HED) laboratory facilities by high power lasers or high current *Z*-pinch discharges. The corresponding laboratory astrophysical experiments were performed using for example GEKKO XII (Fujioka *et al.*, 2009) or Shenguang II (Wei *et al.*, 2008) high-power laser facilities and also Sandia National Laboratory pulsed-power *Z* facility (Bailey *et al.*, 2001; Cohen *et al.*, 2003). In these experiments, the irradiated media were located close to the X-ray radiating plasmas. X-ray power densities in the extreme cases exceeded 10^{11} W/cm^2 and were sufficient for the formation of photo-ionized plasma with high ionization degree. A brief review of interpretation of astrophysical observations, supported by the laboratory astrophysics experiments, was presented by Mancini *et al.* (2009).

Photo-ionized plasmas can also be created using free electron lasers (FEL). In these cases, EUV or soft X-ray photons are emitted in pulses with time duration being several orders of magnitude shorter comparing to X-ray pulses created in HED facilities. Additionally, the radiation can be focused to a small spot with diameter on the order of 10 μm. In such conditions, power density can significantly exceed 10^{14} W/cm^2 allowing for both single- and multi-photon ionization. In such conditions, multiple ionization can be easily obtained, which was shown in many experiments (Moshammer *et al.*, 2007; Richter *et al.*, 2008; 2010; Kurka *et al.*, 2009; Palacios *et al.*, 2010; Sorokin *et al.*, 2007).

In this work, photo-ionized Ne plasmas were created using a low power laser-plasma EUV source and the FEL facility FLASH. However, while radiation fluences in both cases were comparable, a power density obtained with the FLASH laser was approximately 10^7 times higher comparing to the EUV plasma source. Despite this dramatic difference in power density dominating spectral lines in both cases came from neutral and singly ionized atoms. Low intensity spectral lines originated from Ne III ions were also recorded. On the other hand, significant differences in relative line intensities of the emission spectra in the EUV wavelength range were revealed.

EXPERIMENTAL ARRANGEMENTS

The first part of the investigations was performed using a 10-Hz laser-plasma EUV source, based on a double-stream gas-puff target, irradiated with 3-ns/0.8 J Nd:YAG laser pulse. The radiation was focused using a gold-plated grazing incidence ellipsoidal collector (manufactured by Rigaku Innovative Technologies Europe s.r.o., Czech Republic). The collector allowed for effective focusing of radiation emitted from Kr/Xe plasma in the wavelength range $\lambda = 9$ –70 nm. The most intense emission was in the relatively narrow spectral region centered at $\lambda = 11 \pm 1$ nm. The spectral intensity in the longer wavelength range was much smaller; however, the spectrally integrated intensities in both ranges were comparable. The EUV fluence in the focal plane of the collector exceeded 60 mJ/cm^2 at the center of the focal spot and the power density reached 2×10^7 W/cm^2. Detailed description of the source and parameters of the focused EUV radiation can be found elsewhere (Bartnik *et al.*, 2011).

The second part of the investigations was performed using a free electron laser FLASH in Hamburg emitting ultrashort (10 fs duration) pulses at a wavelength of 32 nm. In the experiment, both single bunch and multi-bunch pulses (29 bunches per train with 1 μs pulse separation) were employed at a repetition rate of 5 Hz. Fluence of the focused beam was changing within a range of 0.1–1 J/cm^2 while power density in the focal spot was in the range of 10^{13}–10^{14} W/cm^2.

Ne gas in both cases was injected into the interaction region, perpendicularly to an optical axis of the irradiation system, using an auxiliary gas puff valve. The gas density in the interaction region was controlled by adjustment of either a backing pressure or an opening time of the valve. Additionally, the density could be controlled by choosing a proper distance from a nozzle outlet. Maximum gas density in both cases was 10^{19} atoms/cm^3, however, in case of irradiation using the plasma EUV source density of the irradiated gas was approximately 10–100 times lower.

In both experimental configurations spectral measurements in the extreme/vacuum ultraviolet (EUV/VUV) wavelength range were performed perpendicularly to both the optical axis of the irradiation system and direction of a gas stream. This way the emission spectra of the photo-ionized plasmas were well separated from the spectra of the incident radiation. Resolution of spectrographs was 0.15 nm and 0.08 nm in case of the plasma EUV source and the FLASH laser system respectively. The corresponding wavelength ranges were 27–95 nm and 21–47 nm, respectively. The spectra were integrated over periods of 10 s for the plasma EUV irradiation and 2 to 10 min in case of irradiation with FEL.

Additionally, time duration of plasma EUV pulses and EUV/VUV emission from photo-ionized plasmas produced by these pulses was measured. The measurements were performed using a HS1 detector (from International Radiation Detectors, Inc.). In the first case, the detector was located at a distance of 40 cm from the laser plasma employing a 250 nm thick Be absorption filter ($\lambda \sim 11$–40 nm wavelength range). In the second case, the detector was placed such as to detect radiation of the photo-ionized plasma perpendicular to the optical axis of the irradiation system. Schematic views of both experimental arrangements, showing irradiation and measurement systems, are presented in Figure 1.

EXPERIMENTAL RESULTS

A typical emission spectrum of photo-ionized Ne plasma, created using the plasma EUV source, is presented in Figure 2a. The spectrum, acquired in the full spectral range of the spectrograph, was integrated over a period of 10 s. The spectrum consist of multiple lines originating mainly from transitions in Ne atoms and singly charged Ne ions, however, spectral lines of low intensities corresponding to $2s^22p^4$-$2s2p^5$ transitions in Ne III ions were also detected. The most intense lines correspond to $2s^22p^5$-$2s2p^6$ transition of Ne II ions. The gas density in this case was 5×10^{17} atoms/cm^3. Relative intensities of Ne II and Ne III lines in case of higher densities remained unaltered. The only difference concerned the Ne I $2s^22p^6$-$2s^22p^53s$ lines for which the relative intensities increased up to three times with the gas density. No lines corresponding to Ne IV or higher ionization degree were detected. For estimation of thermodynamic parameters of the photo-ionized plasma, computer spectral simulations were performed using PrismSPECT collisional-radiative code, designed to simulate the atomic and radiative properties of laboratory and astrophysical plasmas (Prism Computational Sciences, Inc.). The resulting calculated spectrum corresponding to experimental data is presented in Figure 2b. Details concerning simulation conditions will be discussed below.

The emission spectrum obtained by irradiation of Ne gas with FEL pulses is shown in Figure 3a. The wavelength range of the acquired spectrum is narrower comparing to the above mentioned and shifted toward shorter wavelengths. Nonetheless, the main part of the spectrum corresponding to transitions in Ne II ions is in the range of the spectrograph. The spectrum does not contain the Ne I lines that are far beyond the long-wavelength limit of the spectrograph. On the other hand, the spectrum contains some additional Ne III lines below 30 nm. Relative intensities of these lines are, however, extremely low. The spectrum was obtained in a single bunch operation mode with energy of the pulse equal to 1 μJ and was integrated over a period of 10 min with repetition rate of 5 Hz. The form of the spectra obtained under other irradiation conditions like multiple bunch operation or higher pulse energy, is similar. The significant difference concerns the relative intensity of a $2s^22p^5$-$2s^22p^4(^3P)3d$ line at $\lambda = 35.6$ nm that is about 30% lower in relation to the single bunch operation mode.

For comparison, part of the spectrum of the EUV induced photo-ionized plasma corresponding to the spectrum obtained with FEL is shown in Figure 3b. While all of the corresponding emission lines are present in both spectra, their relative intensities are different. The most important difference concerns the $2s^22p^5$-$2s2p^6$ lines. The relative intensity of these lines is very low in Figure 3a while in Figure 3b these lines are dominant.

All of the spectral measurements were time integrated. The time duration of the spectrally integrated plasma EUV pulses and emission time of the photo-ionized Ne plasmas created with these pulses are shown in Figure 4. It can be noticed

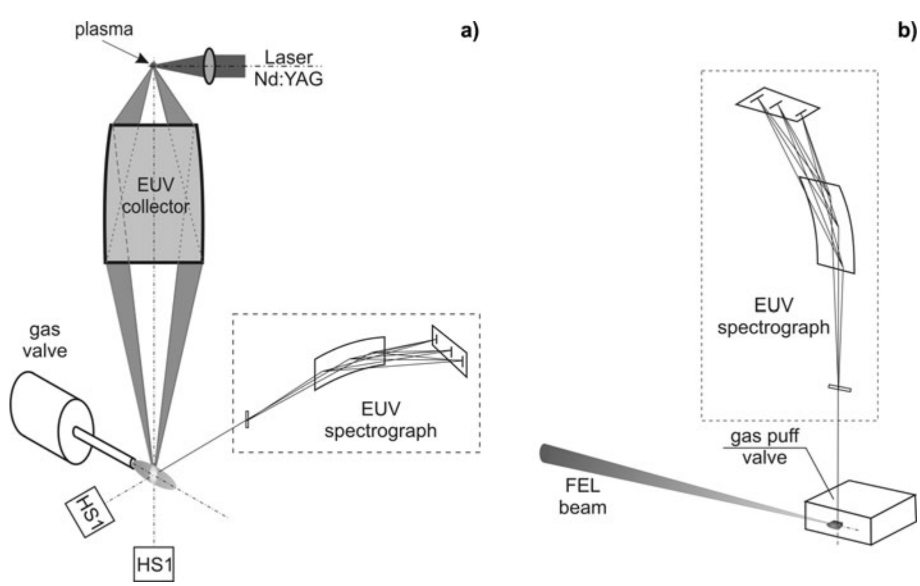

Fig. 1. Schematic views of experimental arrangements for photoionization experiments using: (**a**) laser plasma EUV source, (**b**) free electron laser FLASH.

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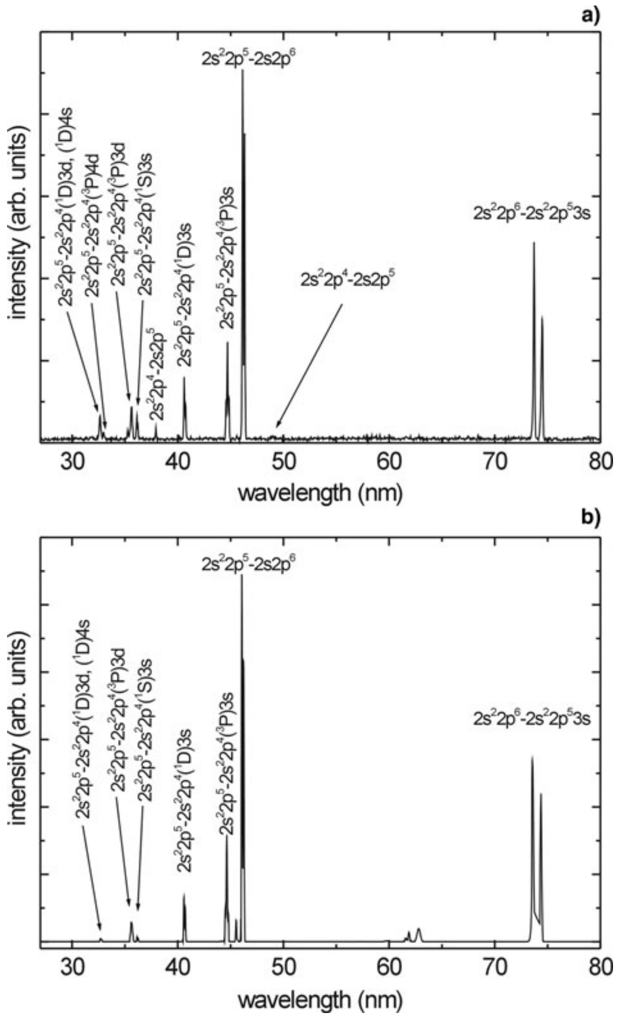

Fig. 2. Ne I–Ne III spectra of the photo-ionized plasma, created by irradiation of neon gas using the laser plasma EUV source: (**a**) measured, (**b**) calculated.

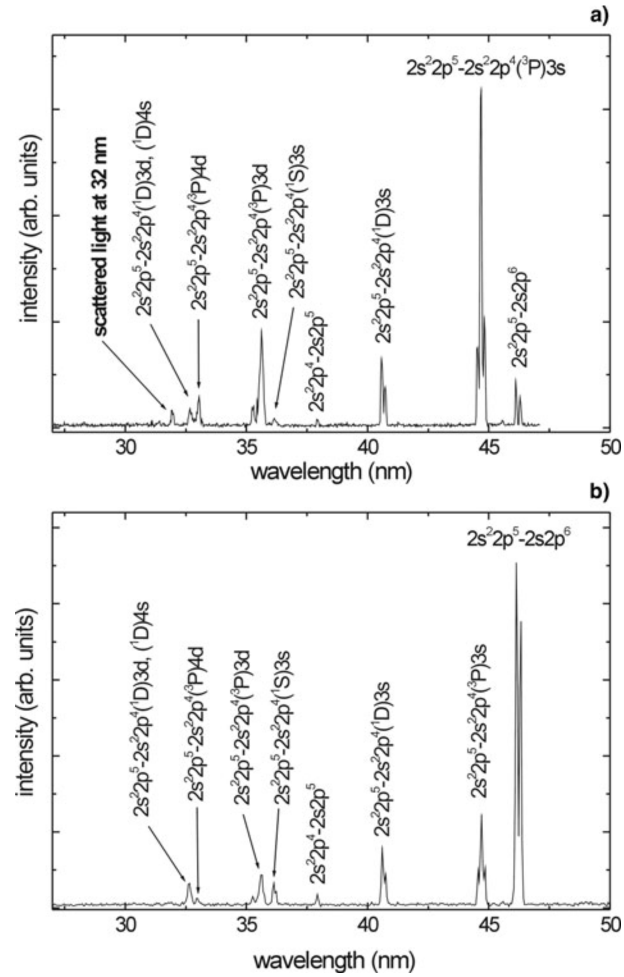

Fig. 3. Spectra of the photo-ionized plasmas created by irradiation of neon gas using: (**a**) the free electron laser FLASH, (**b**) the laser plasma EUV source.

that pulse width of the driving pulse is significantly shorter, 3 ns full width at half maximum (FWHM) comparing to the Ne plasma emission time (5 ns, FWHM). This information was especially important for computer simulation of atomic processes in the photo-ionized Ne plasma.

DISCUSSION

Ionization and excitation processes in Ne gas, driven by EUV radiation are significantly different comparing to laser plasma formation. In the latter case, assuming nanosecond Nd:YAG laser pulses for plasma creation, energy of a single irradiating photon is about 20 times lower than the ionization potential of Ne atoms. In this case, plasma is being heated due to inverse bremsstrahlung mechanism, reaching a high temperature on the order of tens or even hundreds of eV depending on the power density of the laser beam. Energies of thermalized electrons are sufficiently high for ionization of atoms or even multi-charged ions. In such conditions, relative intensities of spectral lines corresponding to particular ion specie do not change significantly with plasma parameters. Significant differences in spectral distributions are mainly associated with the ionization degree, which is strongly dependent on plasma temperature.

In case of irradiation of Ne gas with EUV photons, direct photo-ionization of atoms or even ions by a single photon is possible. Apart from that the energies of the resulting photoelectrons are sufficiently high for further ionization or excitation. Additionally, EUV radiation produced in the Kr/Xe plasma source forms a quasi-continuum because of the large number of possible bound-bound radiation transitions and radiative recombination. In such case, direct photoexcitation of different states is also possible. Radiative deexcitation of the excited states results in linear emission in a wide wavelength range, including the EUV range. In contrast to laser plasmas, energy range of emitted photons is not strictly related to electron temperature. For the same reasons, there is no power density threshold to be exceeded for gas ionization or excitation. There is also no limitation for gas density;

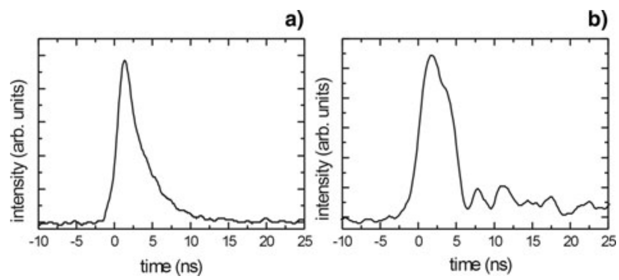

Fig. 4. HS1 detector signals corresponding to EUV emission time profiles: (**a**) laser plasma EUV pulse, (**b**) photo-ionized Ne plasma emission.

however, in case of high density self-absorption of the emitted radiation can be important.

To estimate ionic composition and temperature of the photo-ionized Ne plasma, computer simulations of the atomic processes were performed. The collisional-radiative code used for the simulations includes the following atomic processes: collisional ionization, recombination, excitation, and deexcitation; photoionization and stimulated recombination; photoexcitation and stimulated emission; spontaneous decay, radiative recombination, dielectronic recombination, autoionization, and electron capture. The code also includes Doppler, natural, and Stark broadening in line profile modeling. Atomic levels and transition rates are calculated by ATBASE suite of atomic physics codes.

The computer simulations performed for photo-ionized Ne plasma induced by plasma EUV irradiation were based on different assumptions. First of all, the PrismSPECT code used for the simulations employs a blackbody spectral distribution for an external radiation field. In our experiment, the laser plasma is not a blackbody radiator. On the other hand, spectral distribution of the plasma EUV radiation is quasi-continuous with the maximum at a wavelength close to 11 nm. It was thus approximated by a Planckian radiation with a spectral temperature 20 eV. Another important point concerns the size of the photo-ionized plasma and time development of the atomic processes. The plasma size was assumed to be $d = 1$ mm, taking into account spatial distribution of radiation in the focal spot of the EUV collector (Bartnik *et al.*, 2011) and images of the photo-ionized plasmas (Bartnik *et al.*, 2012). This value, together with the gas density and corresponding cross-sections for atomic processes, determines the possibility of electron thermalization. The problem concerns a mean free path of photoelectrons $l_e = (\sigma n)^{-1}$ in the irradiated gas, where σ is a total cross-section for electron impact ionization and excitation and n is a number of atoms per cm^3. It can be assumed that thermalization is possible in case when $l_e \ll d$. Estimation of the σ value requires information about cross-sections electron impact ionization σ_i and excitation σ_e. These values depend on energy of photoelectrons released during irradiation. Taking into account photon energy $E = 112$ eV, corresponding to maximum intensity of the EUV spectrum (Bartnik *et al.*, 2011), energy of the resulting photo-electron is approximately 90 eV, this is sufficiently high for further ionization or excitation. This value is close to a maximum of energy dependence of cross-section for electron impact ionization of Ne atoms. A corresponding cross-section in this case reaches a value of $\sigma_i = 5 \times 10^{-17}$ cm^2 (Bartlett & Stelbovics, 2002). A total cross-section for excitation of electronic states in Ne atoms is on the order of 10^{-17} cm^2 (Register *et al.*, 1984). The experimental spectrum presented in Figure 2a was obtained for the gas density approximately $n = 5 \times 10^{17} cm^{-3}$. The resulting mean free path of photoelectrons in this case is about 0.4 mm, which is comparable with the photo-ionized plasma size. Additionally, it should be pointed out that irradiation time is comparable with lifetimes of the excited states. It means that electron thermalization in this case is not possible, hence, non- local thermodynamic equilibrium, and non-stationary simulation must be performed. The irradiation time was assumed to be 3 ns and the photo-ionized plasma life time — 5 ns, according to results of the temporal measurements, presented in Figure 4. To perform the calculations an electron temperature T_e must be also assumed. This value combined with some fraction of non-thermal electrons was adjusted to obtain a best fit to the experimental data. The spectrum shown in Figure 3 was calculated for $T_e = 0.3$ eV and 0.4 fraction of non-thermal electrons with energies corresponding to 10 eV electron temperature. The calculated ionic composition in this case is as follows: Ne I = 84.6%, Ne II = 15%, Ne III = 0.4%. Increase of the temperature T_e leads to relative decrease of Ne I line intensities. In turn increase of contribution of non-thermal electrons gives higher intensities at shorter wavelength lines and decrease of intensity of Ne I lines.

The computer simulations were performed only for photo-ionized plasmas created by Ne irradiation with the plasma EUV source. The PrismSPECT code employed for the simulations does not give any possibility to simulate of photo-ionized plasmas induced with intense monochromatic pulses. Apart from the fact that the energy of a single photon in this case is sufficient for ionization of Ne atoms to a $2s^2 2p^5$ state only. Also energy of the resulting photo-electron is too low for further ionization. It means that further ionization requires multi-photon process or electrons must be additionally accelerated in a strong optical field. The mechanism of plasma formation in this case is thus significantly different comparing to the pure photo-ionized plasma. These differences in plasma formation result in significant differences in the emission spectra. In principle, the spectrum obtained in case of plasma induced by FEL pulses contains the same lines as the spectrum of the photo-ionized plasma created using the plasma EUV source. The only exception is a line at $\lambda = 32$ nm, corresponding to the scattered radiation of the FEL beam. The relative intensities of the emission lines in both spectra are significantly different. The main difference concerns intensity of two spectral lines forming a closely-spaced doublet corresponding to $2s^2 2p^5$-$2s2p^6$ transitions. This doublet dominates in case of the pure photo-ionized plasma (Fig. 3b) while in case of the FEL induced plasma the relative intensity of this doublet is very low (Fig. 3a). This difference is directly related to the mechanism of excitation. It should be pointed out that photo-ionization of Ne atoms from the ground state $2s^22p^6$ to the excited state $2s2p^6$ is a single photon, one step process. Excitation of other states in Ne II ions must be preceded by ionization of Ne atoms (Ne I). Thus population of the $2s2p^6$ excited state can be much higher comparing to $2s^22p^5nl$ states especially in non-stationary plasmas. Such situation is observed in the photo-ionized plasmas (Fig. 3b). In case of plasmas created by the free electron laser FLASH, the situation is completely different. Energy of the $2s2p^6$ excited state in respect to the ground state $2s^22p^6$ is 48.475 eV (Schulz *et al.*, 1996) while energy of a single photon in the FLASH laser beam is 38.7 eV. It is thus clear that single photon ionization is not possible in this case. A one step process would require at least two-photon ionization. On the other hand, cross-section for electron impact ionization from the 2s orbital in a wide range of energies is at least an order of magnitude lower comparing to ionization from the 2p orbital (Bartlett & Stelbovics, 2002). It means that there is no reason for preferential population of the $2s2p^6$ excited state, hence, low intensity of the doublet. Concerning other lines, it can be noticed a relative increase of the $2s^22p^5$-$2s^22p^4(^3P)3d$ and $2s^22p^5$-$2s^22p^4(^3P)3s$ line intensities (Fig. 3a) in respect to the corresponding lines for the photo-ionized plasma (Fig. 3b). Such increase was observed in the spectra calculated for the photo-ionized plasmas with strong contribution of non-thermal electrons (>0.5 fraction with energies corresponding to >15 eV electron temperature). It confirms significant contribution of non-thermal electrons in the plasma formation.

SUMMARY

In this paper, first results of investigations concerning photo-ionized Ne plasmas created using a laser-plasma EUV source and a free electron laser FLASH are presented. Significant differences between both experimental configurations concerning the irradiation conditions are indicated. The emission EUV spectra of the excited atoms and singly or doubly charged Ne ions were registered. Computer simulations of the photo-ionized plasmas induced by the laser plasma EUV pulses were performed using a collisional — radiative Prism-SPECT code. Good agreement between the measured and calculated spectra was obtained. Significant differences between spectra obtained in both experimental configurations were revealed. Atomic processes dominating in both types of plasmas were analyzed. It was concluded that plasma induced by the high intensity FEL pulses at the wavelength of 32 nm should not be regarded as purely photo-ionized.

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