# Structure and Intensity of X-ray Radiation in a Laser Plasma–Wall Interaction

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## ABSTRACT

Intense soft x-ray radiation is observed when a high temperature laser produced plasma collides with a solid surface (wall). The laser plasma is produced by *Nd:YAG* laser radiation (0.53 μm; 200 mJ; 3 ns; $5 \cdot 10^{12}$ W/cm$^2$) focused onto a Mg target. The wall is placed in the path of the plasma expansion. Two experimental techniques are used: 1. One-dimensional x-ray images of the plasma-wall gap formed by a slit are observed using an absolutely calibrated CCD linear array. 2. X-ray spectra of *[H]-* and *[He]*-like *Mg* ions are recorded using a crystal focusing x-ray von Hamos spectrometer. At a measured electron temperature of $T_e$=195 eV, emission of *[He]-* like ions *Mg XI* gives the main contribution to the observed x-ray intensity. The spatial structure and the intensity of the radiation are studied at various laser plasma-wall distances ($r_0$=0.3 – 3.0 mm). Intense radiation near the wall is caused by an electron density jump in a shockwave formed in front of the wall. At small wall distances $r_0 << v\tau$ (v is the expansion velocity, $\tau$ is the laser pulse duration) the radiation is caused by excitation processes, and at distances $r_0$<0.3 mm the near wall intensity exceeds the emission from the laser plasma itself. At distances $r_0 >> v\tau$ the radiation causes recombination processes. These results are important for developing collision and recombination schemes for x-ray lasers in colliding plasmas.

Keywords: laser plasma-wall interaction, x-ray spectroscopy, and x-ray lasers.

## 1. INTRODUCTION

The interaction of high-temperature plasmas containing highly charged ions with solid walls has attracted theoretical and experimental interest. Of particular importance is the investigation of the effects of solids on the properties of expanding laser produced plasmas. Some new challenges in this area are the feasibility of the creation of intense soft x-ray radiation sources,[1-3] the development of black-body radiation sources with a radiative temperature of about 100 eV and higher,[4-6] and the formation of active media for x-ray lasers.[7-17]

Intense line emission of highly charged ions in the laser plasma-wall interaction was observed for the first time in Ref. [1] and later in Refs. [2, 3, 8-10, 16], where the spatial-temporal structure of radiation and the spectra of highly charged ions were studied in both the visible and soft x-ray spectral regions.

The present work focuses on the study of the laser plasma-wall interaction at different plasma-wall distances ($r_0$=0.3-3 mm). The structure and intensity of the radiation as well as the x-ray spectra of the *[He]*-like *Mg* ions are investigated. The study allows us to distinguish the different processes (excitation and recombination) which are responsible for near-wall emission.

## 2. EXPERIMENT

The experiments were performed using a *Nd-YAG* laser—"Infinity" (0.53 μm/ 200 mJ/ 3 ns). The laser beam was focused by an f/4 lens onto a magnesium target oriented at 45° from the axis of the incident laser beam (see Fig. 1). The focal spot diameter was ~60 μm, corresponding to a laser intensity of ~$3 \cdot 10^{12}$ W/cm$^2$. A flat aluminum obstacle (the "wall") was placed parallel to the target surface on the path of the laser-produced plasma expansion. The wall surface area was 1.3 mm x 1.3 mm. The distance $r_0$ between the target and the wall was varied from 0.3 mm to 3 mm. The wall was installed in such as not to intersect the laser radiation reflected from the target.

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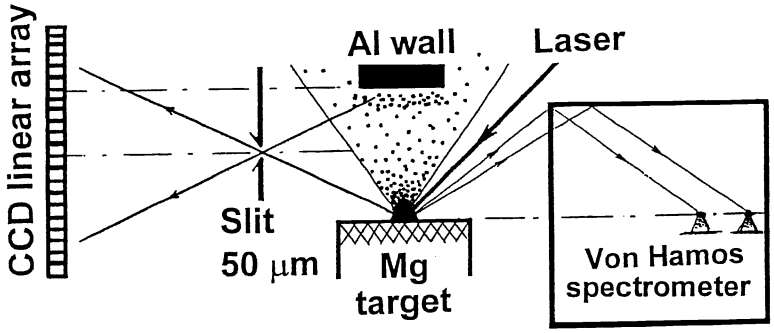



Fig. 1. Schematic diagram of the experiment.

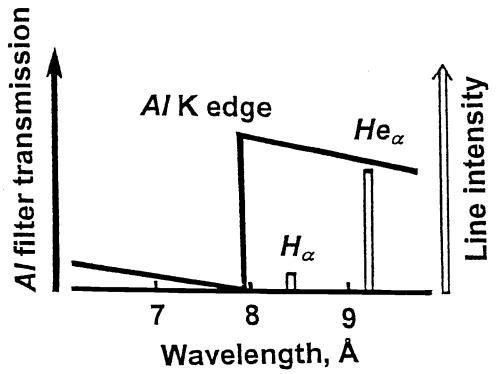



Fig. 2. Principle of wavelength selection.

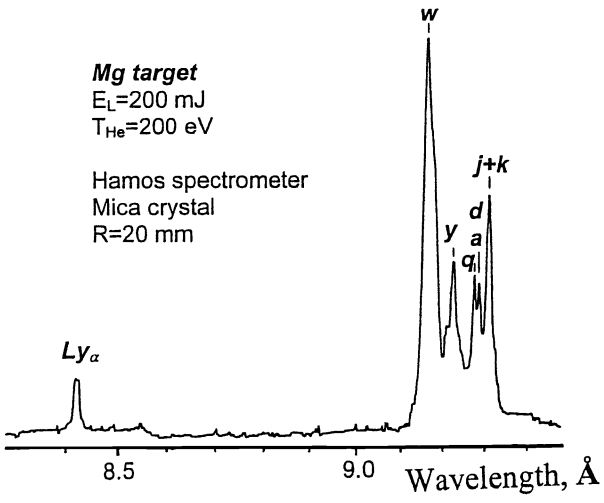



Fig. 3. Microdensitometer tracing of highly charged *Mg* ions in laser-produced plasma recorded by the von Hamos spectrometer.



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The time integrated spatial profile and the intensity of the x-ray radiation in the laser plasma-wall interaction were investigated using two experimental instruments: 1. A CCD linear array x-ray detector, and 2. an x-ray focusing crystal von Hamos spectrometer. The 1D x-ray image of the plasma-wall gap formed by a slit was observed using an absolutely calibrated CCD linear array.[18] The commercial CCD (Toshiba model TCD 1304AP) is a linear array with 3724 pixels. Each pixel is 8 μm wide (6 μm active) and 200 μm in height. The total effective detection area is 200 μm by 29.8 mm (8 μm x 3724 elements). The front cover glass is removed for x-ray detection. To prevent visible light illumination, an *Al*-coated mylar filter (4.4 μm of mylar, 0.2 μm of *Al*) was used. A 50 μm slit was installed in two positions: 1. between laser-produced plasma and the wall to record the intensity profile of the plasma-wall gap; and 2. along the wall surface to investigate the radiation structure near the wall (see Fig. 1). Magnification in both cases was ~5X. In the experiments, radiation near the resonance line of the *[He]*-like *Mg* ions was detected. A special combination of laser target and x-ray filters was used to make this measurement.[18,19] The *Al* foil, 6.25 μm thickness, was used as an x-ray filter in front of the CCD. In combination with the *Mg* target, this filter selected the line radiation near resonance lines of *[H]*-and *[He]*-like ions (see Fig. 2). Under the experimental conditions used mainly *[He]*-like ions were excited (see below). The contribution of the continuum spectra was small (about 20% of the total intensity[18,19]).

The x-ray spectra of *[H]*-and *[He]*-like *Mg* ions in the laser-produced plasmas and in the near wall region were investigated using a focusing crystal von Hamos spectrometer[19,20] The image of the plasma-wall gap was observed simultaneously with spectral information. These spectra were used for determination of plasma parameters—electron temperature and density, and source size. The spectrometer possesses several distinct advantages. These include high spectral resolution, direct registration of two dimensional source images, and high detection efficiency over a wide spectral range.[19] A mica crystal (2d=19.84 Å, radius of curvature R=20 mm) was used in the von Hamos spectrometer. X-ray spectra were recorded using Kodak RAR 2492 x-ray photographic film.[21] A 4.4 μm thickness of mylar foil with a 0.3 μm thickness of *Al* was used as an x-ray filter. The spectrometer axis was aligned along the *Mg* target surface (see Fig. 1). The spectral resolution of the spectrometer was defined by the source size. For the laser-produced plasma itself the value of the spectral resolution, $\lambda/\delta\lambda$, was equal to $\lambda/\delta\lambda$~700. For the near wall region, $\lambda/\delta\lambda$~80-150, spectra were recorded at target-wall distances of $r_o$=0.5-1.0 mm.

## 3. RESULTS AND DISCUSSIONS

The von Hamos spectrometer imaged the plasma-wall gap in each spectral line. In these images it is possible to observe two pertinent zones of soft x-ray emission, which are separated spatially. The first zone is in the immediate vicinity of the *Mg* target; it corresponds to the laser-produced plasma itself. The intense emission extends up to a distance of 100-200 μm from the target surface and decays at a larger distance. The second zone is located near the wall where the expanded laser plasma reaches the *Al* wall; this is the interaction zone. A similar emission structure was observed in Refs. [1-3].

The spectral resolution (see Fig. 3) enabled us to determine some of the plasma parameters in laser-produced plasmas (zone I). The laser plasma source size on the target was equal to ~150 μm. From the spectral images, the angle of laser plasma expansion was determined (~70°). The electron temperature, $T_e$, in the plasma was deduced from the intensity ratio of the dielectronic satellites *k, j* to the resonance line *w* of the *[He]*-like ions[22,23] (see Fig. 4). The mean temperature value was estimated to be $T_e$ = (195±15) eV. The intensity ratio of the resonance lines of *[H]*- and *[He]*-likes ions, which characterizes the relative ion concentrations, was found to be 0.1±0.02.

In the near wall region (zone II) intense radiation in the lines of *[He]*-like *Mg* ions was observed. An important feature of the spectra is the presence of satellite lines, which were absent in Refs. [1-3]. This feature indicates that at the small distances ($r_o$=0.5-1.0 mm) emission near the wall results from excitation processes in contrast to recombination processes in Refs. [2,3]. The electron temperature measured in the near wall region was higher than in the laser-produced plasmas itself: $T_e$ = (315±35) eV at $r_o$ = 0.5 mm and $T_e$ = (230±20) eV at $r_o$ = 1.0 mm.

The same emission zones were clearly observed in the 1D images recorded by the CCD linear array (see Fig. 5). The near-wall x-ray intensity increases when the plasma-wall distance $r_o$ is reduced. At the distance $r_o$~0.3 mm, the intensity is comparable to the laser-produced plasma itself. The intensity ratio of the near wall emission to the laser-produced plasma emission is shown in Fig. 5. The near-wall intensity is normalized to the total cross section of the expanding laser plasma in the interaction zone. At small distances $r_o$ the intensity ratio scales as $(r_o)^{-2}$. The intensity curve shows a bend at $r_o$~1.0 mm, and further the intensity slightly changes with the distance $r_o$. The behavior at large distances $r_o$ indicates that other processes are responsible for the near-wall emission.



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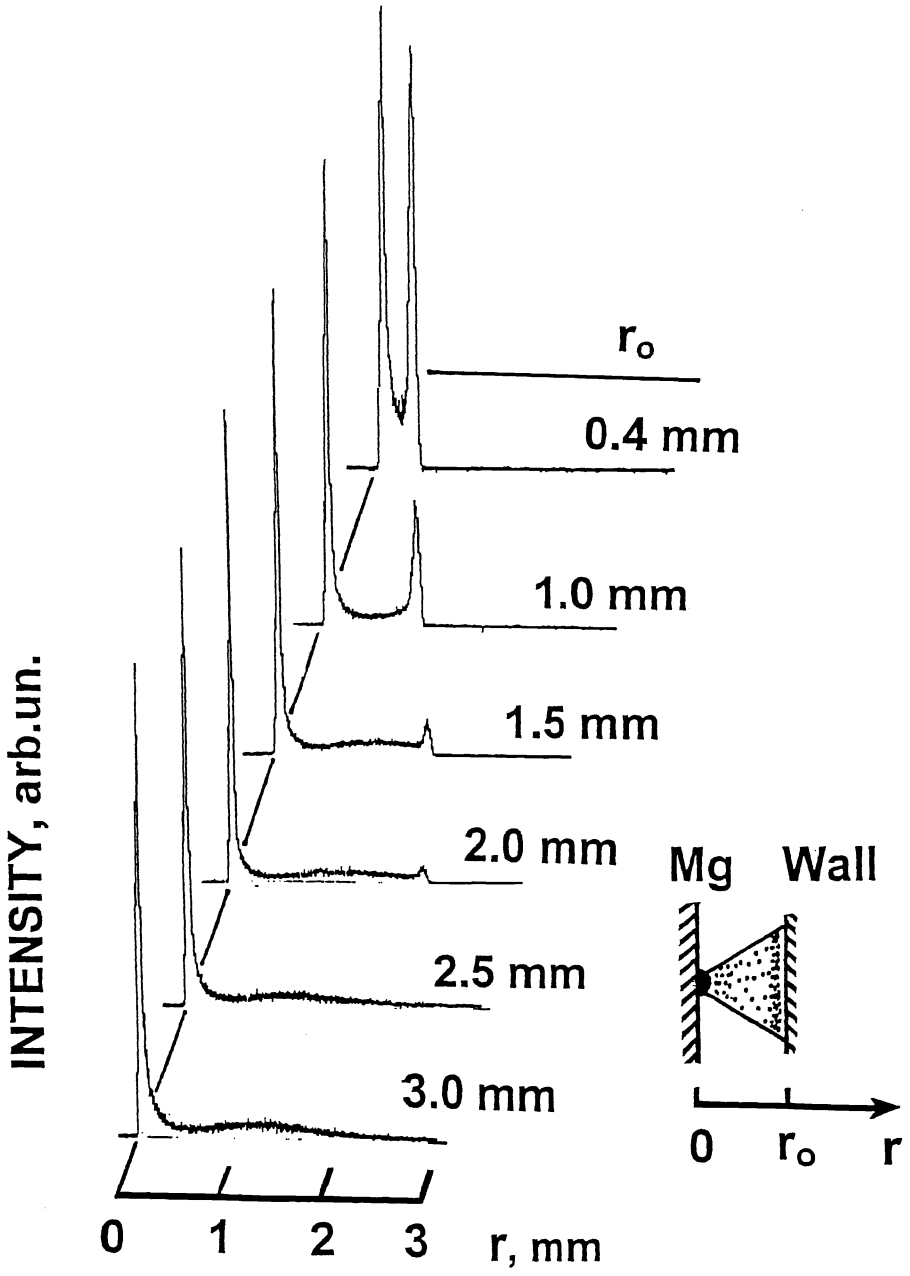



Fig. 4. Spatial structure of x-ray intensity in a laser plasma–wall gap recorded by the CCD linear array.



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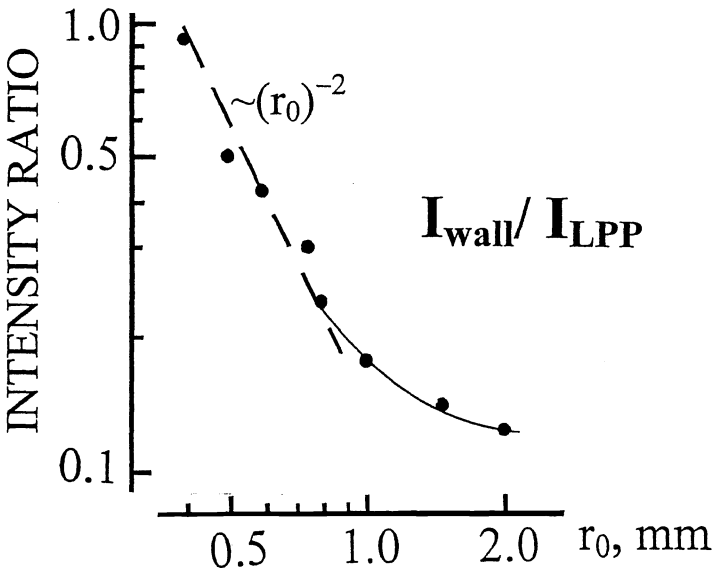



Fig. 5. Intensity ratio of the near wall radiation to radiation of laser-produced plasma versus plasma–wall distances $r_0$.

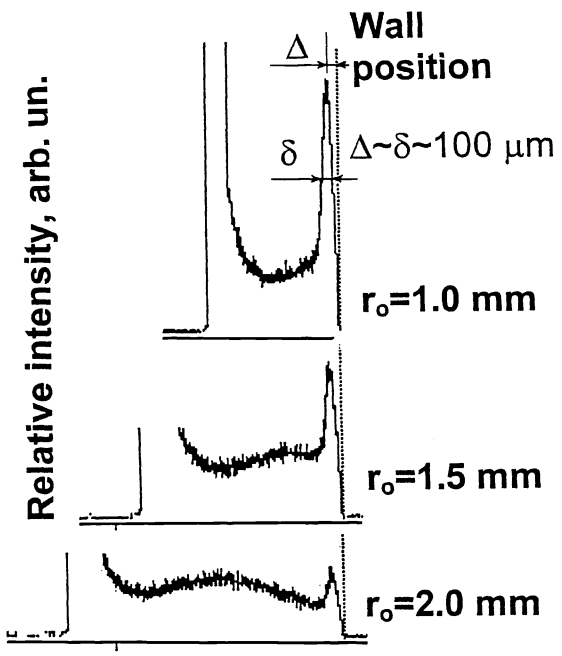



Fig. 6. Structure of radiation near the wall at various plasma-wall distances $r_0$.



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The intensity profile near the wall is shown in Fig. 6. The maximum intensity is observed at a distance of ~100 μm from the wall. The characteristic feature of the near-wall emission is the presence of an additional dip in the intensity curve, which is observed before the maximum intensity at distances $r_o$>1.5 mm.

To explain the experimental results it is necessary to take into account the parameters and structure of the shock wave formed near the wall. When the laser plasma flux interacts with an obstacle (wall), a shockwave is created near the obstacle. The shock wave front moves toward the incidence plasma flux.[2] The structure and the parameters of shock waves in plasma are considered in Refs. [24, 25]. In addition to the usual density jump in a shockwave, there is a region of smooth temperature change. In front of the jump there is a region of raised electron temperature due to the high electron thermal conductivity.

The density jump and the increase in the electron temperature in the shockwave front, as well as the presence of a preheating "foot" ahead of the shock is due to electron thermal conductivity, explain the intensity profile of the x-ray emission near the wall. The density jump increases the rates of both the collision and the recombination processes, leading to intense emission of *[He]*-like ions near the wall. However, the processes, which are responsible for the observed emission, are different at various $r_o$ distances. The various regimes observed in the experiment can be interpreted via the parameter of plasma jet length, $v_0\tau$, where $v_0$ is the unperturbed plasma jet expansion velocity, and $\tau$ is the laser pulse duration. In our case $v_0 \sim 2 \cdot 10^7$ cm/s (for $T_e$ = 195 eV), $\tau$=3 ns, and the parameter $v_0\tau$=0.65 mm.

At small plasma-wall distances $r_o << v_0\tau$, the laser-heated plasma follows an isothermal expansion. When the plasma jet interacts with the wall, an electron density jump in the shockwave takes place. The electron temperature observed in the shockwave front near the wall is the same or even higher than in laser-produced plasmas (see above). Both of theses effects suggest an excitation rate proportional to $\exp(-\Delta E/kT_e)$,[23] where $\Delta E$ is the excitation energy. For example, for resonance transition in *[He]*-like *Mg* ion $\Delta E$ is equal to 1.35 keV. This occurs in the near-wall plasma and results in an increase of the line intensities of the *[He]*-like Mg ions. The processes are similar to those in the laser-produced plasma itself, when lines of *[He]*-like ions and accompanying satellites are observed in the spectra.

At plasma-wall distances of $r_o >> v_0\tau$, the laser plasma follows adiabatic expansion, and the electron temperature $T_e$ falls rapidly ($T_e \sim r_o^{-1} - r_o^{-2}$).[26] The increase of $T_e$ in the shockwave is not enough to excite levels from the ground state of *[He]*-like ions. In this case three-body recombination takes place (the recombination rate $\sim T_e^{-9/2}$):[27] *[H]*-like ions recombine to *[He]*-like when highly excited levels of *[He]*-like ions are populated. Subsequent cascade transitions due to collision and radiative processes lead to x-ray line emission of *[He]*-like ions. The observed intensity ratio (see Fig. 5) corresponds approximately to the concentration ratio of the *[H]*- and *[He]*-like ions in laser-produced plasma. For this reason this intensity ratio does not depend strongly on the distance, $r_o$, as observed in Fig. 5. The recombination character of the radiation is confirmed by the presence of an additional dip in the intensity at $r_o$>1.5 mm (see Fig. 6). The preheating "foot" ahead of the shockwave due to electron thermal conductivity leads to a decrease of the recombination rate ($\sim T_e^{-9/2}$), and hence to a decrease of the line intensities. Note that the same preheating "foot" leads to an increase of the excitation rate $\{\sim\exp(-\Delta E/kT_e)\}$, and this dip is not observed at small $r_o$ (see Fig. 6).

## 4. CONCLUSIONS

The spatial profile and the intensity of x-ray radiation are studied at various laser plasma-wall distances ($r_0$=0.3-3.0 mm). It is shown that radiation near the wall is caused by an electron density jump in a shock wave formed near the wall. At small wall distances, $r_0 << v\tau$ (v is the expansion velocity, $\tau$ is the laser pulse duration) the radiation is caused by excitation processes, and at distances $r_0$<0.3 mm the near-wall intensity exceeds that of the laser plasma itself. At distances $r_0 >> v\tau$, the radiation is caused mainly by recombination processes. These results are important for developing collision and recombination schemes for x-ray lasers in colliding plasmas.

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## REFERENCES


1. L. P. Presnyakov and A. P. Shevelko, "Intense x-ray emission in the interaction of the laser-plasma with a solid surface," *JETP Lett.* **36**, pp. 44-47, 1982.
2. M. A. Mazing, P. Ya. Pirogovski, A .P. Shevelko, and L. P. Presnyakov, "Interaction of a laser-produced plasma with a solid surface," *Phys. Rev.* **A 32**, pp. 3695-3698, 1985.
3. I. L. Beigman, P. Ya. Pirogovskiy, L. P. Presnyakov, A. P. Shevelko, and D. B. Uskov, "Interaction of a laser-produced plasma with a solid surface: soft x-ray spectroscopy of high-Z ions in a cool dense plasma," *J. Phys. B: At. Mol. Opt. Phys.* **22**, pp. 2493-2502, 1989.
4. K. Okada, T. Mochizuki, N. Ikada, M. Hamada, M. Mineo, R. Kodama, and C. Yamanaka, "Energy confinement effect on the soft x-ray generation in 0.535 μm laser-heated cavity target," *J. Appl. Phys.* **59**, pp. 2332-2336, 1986.
5. S. Sakabe, R. Sigel, G. D. Tsakiris, I. B. Földes, and P. Herrmann, "X-ray generation in a cavity heated by 1.3-0.44 μm laser light I, II, III," *Phys. Rev.* **A38**, pp. 5756-5786, 1988.
6. H. Nishimura, Y. Kato, H. Takabe, T. Endo, K. Kondo, H. Shiraga, S. Sakabe, T. Jitsuno, M. Takagi, C. Yamanaka, S. Nakai, R. Sigel, G. D. Tsakiris, J. Massen, M. Murakami, F. Lavarenne, R. Fedosejevs, J. Meyer-ter-Vehn, K. Eidmann, and S. Witkowski, "X-ray confinement in a gold cavity heated by 351-nm laser light," *Phys. Rev.* **A44**, pp. 8323-8333, 1991.
7. S. Suckewer, C. H. Skinner, H. Milchberg, C. Kean, and D. Voores, "Amplification of stimulated soft x-ray emission in a confined plasma column," *Phys. Rev. Lett.* **55**, pp. 1753-1756, 1985.
8. V. A. Boiko, F. V. Bunkin, V. I. Derzhiev, and S. I. Yakovlenko, "Possibilities of Amplification of Ultraviolet and Soft X-Ray Radiation on Multiply Charged Ion Transitions in a Recombining Plasma," *IEEE J. Quantum Electron.* **QE-20**, pp. 206-217, 1984.
9. R. Kodama and T. Mochizuki, "Population inversion in laser-produced plasmas stagnating on a radiative coolant of solid density," *Optics Letters* **12**, pp. 990-992, 1987.
10. T. Boehly, P. Audebert, D. Shvarts, B. Yaakobi, B. Boswell, D. Bradley, R. S. Craxton, R. Epstein, M. C. Richardson and J. M. Soures, "Experimental Studies of New Geometries for X-ray Laser Experiments," *SPIE* **831**, pp. 305-320, 1987.
11. W. Tan, Z. Lin, W. Yu, M. Gu, W. Chen, Y. Zheng, G. Wang, J. Cui, and X. Deng, "High population inversion in the soft-x-ray band observed in a laser-irradiated microtube," *J. Appl. Phys.* **64**, pp. 6128-6131, 1988.
12. E. Miura, H. Daido, Y. Kitagawa, K. Sawai, Y. Kato, K. Nishihara, S. Nakai, and C. Yamanaka, "Gain measurements of the CVI 3d-2p transition (18.2 nm) from wall confined carbon plasmas produced by a $CO_2$ laser," *Appl. Phys. Lett.* **55**, pp. 223-225, 1989.
13. H. Daido, K. Nishihara, E. Miura, and S. Nakai, "Simulation of recombination-pumped soft-x-ray lasers in wall-confined laser-produced plasmas," *J. Opt. Soc. Am.* **B7**, pp. 266-271, 1990.
14. L. P. Presnyakov, A. P. Shevelko, and D. B. Uskov, "Soft X-ray spectroscopy of high-Z ions in a cool and dense plasma," *Z. Phys D. -Atoms Mol. and Clusters* **21**, pp. 157-158, 1991.
15. C. Stockl and G. D. Tsakiris, "Experiments with laser irradiated cylindrical targets," *Laser Part. Beams* **9**, pp. 725-737, 1991.
16. J. R. Crespo Lopez-Urrutia, E. E. Fill, R. Bruch, and D. Schneider, "Laser-plasma ion sources: application to charge-transfer X-ray lasers," *Nucl. Instrum. Meth.* **B79**, pp. 705-707, 1993.
17. R. W. Clark, J. Davis, A. L. Velikovich, and K. G. Whitney, "X-ray lasing in colliding plasmas," *Phys. Plasmas* **4**, pp. 3718-3724, 1997.
18. A. P. Shevelko, L. V. Knight, Q. Wang, and O. F. Yakushev, "Absolute x-ray calibration of laser-produced plasmas using CCD linear array and focusing crystal spectrometer," *SPIE* **4504**, 2001.
19. A. P. Shevelko, "X-ray spectroscopy of laser-produced plasmas using a von Hamos spectrograph," *SPIE* **3406**, pp. 91-108, 1998.
20. Von L. v. Hámos, "Röntgenspektroskopie und Abbildung mittels gekrùmmter Kristallreflektoren," *Ann. Phys.* **17**, pp. 716-724, 1933.
21. B. L. Henke, F. G. Fujiwara, M. A. Tester, C. H. Dittmore, and M. A. Palmer, "Low-energy x-ray response of photographic films. II. Experimental characterization," *J. Opt. Soc. Am.* **B1**, pp. 828-849, 1984.
22. A. H. Gabriel, "Dielectronic satellite spectra for highly charged helium-like ion lines," *Mon. Not. R. Astron. Soc.* **160**, pp. 99-119, 1972.
23. L. A. Vainshtein, U. I. Safronova, and A. M. Urnov, "Dielectronic satellites of resonance lines of highly charged ions," *Proceedings of the Lebedev Physical Institute,* Nova Science Publishers, ed. N. G. Basov, **119**, 1980.
24. Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, pp. 515-522, Academic Press, New York, 1966.
25. V. D. Shafranov, "Structure of shock waves in a plasma," *Sov. Phys. JETP* **5**, pp. 1183-1188, 1957.




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26. P. T. Rumsby and J. W. M. Paul, "Temperature and density of expanding laser produced plasma," *Plasma Phys.* **16**, pp. 247-260, 1974.
27. Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, pp. 406-412, Academic Press, New York, 1966.



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