Proposal for the X-ray laser pumped by a powerful short-pulse drive laser

Elena P.Ivanova, Arkadi L. Ivanov, Nick A. Zinov'ev

Institute of spectroscopy of Russian Academy of Sciences, Troitsk, Moscow Region, 142092

Larry V. Knight

Brigham Young University, E S C, Provo, Utah, 84204

ABSTRACT

Within accurate atomic kinetic model it is shown that the inversion state of heavy Ne-like ions in plasma is possible at electron densities $n_e > 10^{23}$ cm^{-3} if electron temperature is high enough ($T_e > E_{ioniz}/2$). Near optimum plasma conditions are found for Ne-like silver lasers. New effective lasing transitions in Ne-like silver are found. Large ASE effect (gL > 100) is predicted for Ne-like silver plasma produced by a powerful short-pulse drive laser.

Keywords: X-ray lasers, multicharged ions, spectra modeling, atomic-kinetics calculations

1. INTRODUCTION

Presently the technique of chirped pulse enhancement has permitted the generation of laser systems with peak power more than 10^{15} W and the main pulse to prepulse intensity ratio more than 10^{8} [1]. This pulse can be focused on an oblong target (Fig.1), it can drive highly nonequilibrium plasma. The interaction between the short laser pulses and the solid materials has been extensively studied by experiments and theories. The target plasma temperature, density distribution and their evolution depends of many factors like pulse to prepulse ratio, pulse duration, its wavelength, angle of incidence etc. Of particular significance is target fabrication - deposition method, thickness, surface conditions and so on. If the laser pulse is short enough (FWHM ≤ 1 ps) , and target thickness (D) is of the order of pulse wavelength, then the laser produced plasma expansion will be small enough during the energy deposition, and production of high density plasmas with a sharp density gradient becomes possible [1-4]. At a very high laser intensities ($I > 10^{17}$ W/cm^2), the radiation pressure of a high-contrast pulse (ponderomotive forces) will tend to balance thermal pressure during the laser energy deposition, allowing one to achieve isochoric heating at nearly solid density, up to very high electron temperatures (multi - keV range).

Methods to increase the radiant power of x-ray sources from ultrashort-pulse laser-produced plasmas are a topic of considerable current interest. Physical parameters that control x-ray pulse duration have been discussed in theoretical research, including the effects of plasma expansion and thermal conductivity. Numerical results of the work [3] confirm the collisional dependence of x-ray pulse duration. This work has proved that pulse width of the laser produced x-rays emitted from solid targets may be varied in wide limits (10 - 100 ps) depending on plasma density and drive laser intensity. Thus increased efficiency for x-ray production results from the high intensity of drive pulse because optical field ionization becomes a key mechanism for plasma production and heating. Electron acceleration in the optical field and electron absorption of laser pulse photons (reverse bremsstrahlung) are other key processes that drive plasma collisional ionization and heating. Plasma density can be controlled with drive pulse contrast and duration. From the experiments and MHD simulations of high intensity laser pulse - solid target (D < 1μ,) interaction it follows that there are two stages for target plasma evolution after irradiation. At the first stage overheated target bursts with rapid expansion and cooling; time duration for this stage is 1-2 ps, and target plasma radius increases by 1-3 μm. At the second stage further expansion is much slower, thus it is stage of plasma stagnation when principal cooling mechanism is x-ray emission. Plasma density evolution during the first stage (picosecond dynamics) of a hot solid-density plasma was investigated in [2]. In this work the time history of multi - keV x-ray emission was studied with a streak camera having 1.6-ps temporal resolution. Time-resolved Al Li-like spectra were measured showing the variation of the line shape with time. The calculations of Stark broadening for $1s2l2l' - 1s^2 2l$ line allowed to determine the evolution of plasma density. Resuming the experiments [1-4] one concludes that after burst at stagnation plasma is uniform with very steep density gradient on the edge (δ); the thickness of this plasma layer δ is much smaller than the drive pulse wavelength: $\delta << 1$ μm.

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The idea of-using a femtosecond drive-pumping pulse for an X-ray laser creation was realized in practice by two groups: Nagata et al. [5] and Lemoff et al. [6]. In one case the ASE effect was measured with a gain value 20 cm^{-1} on Lyman-alpha transition at 13.5 nm in H-like lithium. In the other work, a collisional-radiative model of VUV lasing was realized at the Pd-like xenon transition $4d^95d\ ^1S_0$ - $4d^95p\ ^1P_1$ at wavelength 41.8 nm [6].

In the previous paper [7] we have shown that large gain values (gL > 100) are achievable an a hot dense quasi-steady-state silver plasma at λ = 10.038 nm (23-11 J=2 - J=1) and at λ = 12.298 nm (21 - 11 J=0 - J=1). It was proved that lasing is also possible at innershell 2s - 2p transition with λ = 2.75 nm (29 -3 J=0 - J=1). The choice of a Ne-like silver plasma as the focus of our study is based on an experimental study of lasing in a silver plasma done using the NOVA laser facility at Lawrence Livermore National Laboratory (LLNL) [8]. Two opposite beams: 0.53 μm, 500 ps wide Gaussian pulses, intensity $I = (5 - 15)\times10^{14}$ W/cm^2 were focused at line of silver foil: 100 - 200 $\mu g/cm^2$, length 0.40 - 0.89 cm. Electron density at lasing was estimated as $n_e = 10^{21}$ cm^{-3}. Gain values were measured for two transitions: $g \approx 9.4$ cm^{-1} at λ = 9.9365 nm (J=2 - J=1 transition) , and $g \approx 6.4$ cm^{-1} at λ = 10.038 nm (another J=2 - J=1 transition).

Recently we reviewed the previous gain calculations for Ne-like silver plasma and found that large inversion and gain values are possible for many other transitions. They are listed in Table 1. In the top part of the Table 1 the ordinary transitions are listed with low active levels: $2p^53s$ [J=1]. The new transitions are in the bottom part of the Table 1. There are some 3d - 3p transitions (spectator is 2p or 2s), and 3p - 3s transitions (spectator is 2s) . They were not considered earlier for the reason that these are transitions between highly excited states, which were supposed to be less populated at moderate electron temperatures. On the other hand they are not effective at low electron densities $n_e \leq 10^{21}$ cm^{-3}. In this paper we calculate gain values for all possible transitions in Ne-like silver plasma as functions of electron density and energy. For each transition the optimum plasma conditions are found. We discuss also the necessary drive-laser-pulse parameters for this sort of plasma production. Fig. 1 shows schematically the short-drive-pulse-pumping experiment for the Ne-like silver X-ray laser.

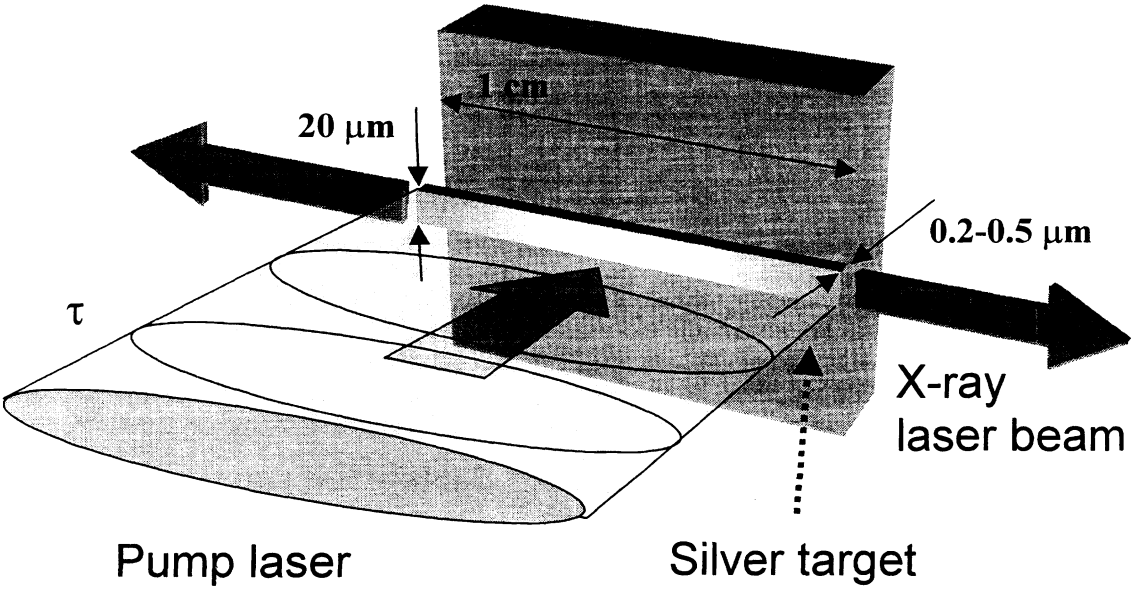


Fig.1. Schematic diagram of the pumping and x-ray lasers configuration.

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TABLE 1. Transitions in Ne-like silver, lasing at definite plasma conditions. Levels are designated by order numbers. For each transition the wavelength (λ, A) and the radiative transition probability from upper state to lower (RTP, s^{-1}) are given.

Transition		order numbers	λ (A) Present work	λ (A) Exp.[8]	RTP (s^{-1}) Present work
Upper state	Lower state				
2p3/23p3/2[J=2]	**2p3/23s1/2[J=1]**	**8 - 3**	**99.53**	**99.37**	**3.06+10**
2p3/23p3/2[J=0]	2p3/23s1/2[J=1]	9 - 3	80.932	80.156	5.99+10
2p3/23d5/2[J=2]	2p3/23p3/2[J=1]	17 - 7	113.8		2.59+10
2p1/23p1/2[J=1]	2p1/23s1/2[J=1]	20 - 11	167.11		1.04+10
2p1/23p1/2[J=0]	2p1/23s1/2[J=1]	21 - 11	121.36	123.00	1.51+10
2p1/23p1/2[J=1]	2p1/23s1/2[J=1]	22 - 11	102.2		2.02+10
2p1/23p3/2[J=2]	**2p1/23s1/2[J=1]**	**23 - 11**	**100.47**	**100.37**	**6.12+10**
2s1/23s1/2[J=0]	2p3/23s1/2[J=1]	29 - 3	27.5		5.15+11
2p1/23d3/2[J=2]	2p1/23p1/2[J=1]	24 - 20	86.310		6.64+10
2p1/23d5/2[J=2]	2p1/23p3/2[J=1]	25 - 22	115.3		3.27+10
2p1/23d5/2[J=3]	2p1/23p3/2[J=2]	26 - 23	113.3		3.63+10
2s1/23p3/2[J=2]	2s1/23s1/2[J=1]	32 - 28	100.63		6.16+10
2s1/23d3/2[J=1]	2s1/23p1/2[J=1]	34 - 31	89.229		2.31+10
2s1/23d3/2[J=2]	2s1/23p1/2[J=1]	35 - 31	87.813		5.87+10
2s1/23d5/2[J=3]	2s1/23p3/2[J=2]	36 - 32	119.1		3.63+10
2s1/23d5/2[J=2]	2s1/23p1/2[J=1]	37 - 31	77.577		6.94+09
2s1/23d5/2[J=2]	2s1/23p3/2[J=1]	37 - 33	111.6		3.28+10

2. GAIN COEFFICIENT CALCULATIONS

In the first approximation MHD, atomic-kinetic and light propagation calculations can be considered independently. The central problem - accurate atomic-kinetic calculations for steady-state uniform plasma is under present consideration. The method was elaborated in [9] to calculate precisely spectra of plasma containing two ionization stage: Ne-like and Na-like. Here we give its brief description. Uniform steady-state plasma can be described with only 5 parameters: electron and ion temperatures: T_e, T_i; their densities n_e, n_i and plasma thickness d. We solve the set of balance equations for the level populations with some definite initial values; level populations of two adjacent ionization stages: Ne-like and Na-like are included in the balance equations. As a result we obtain the kinetics for the ionization balance, for the level populations, for the inversion and for the gain values at given plasma conditions. Rate coefficients for the radiative-collisional transitions between 37 levels $2p^53l$, $2s2p^63l$ of Ne-like silver are calculated precisely on the basis of the consistent QED approach [10-13]. The accounting for the multitude of the Rydberg and autoionizing Rydberg series of Na-like ions gives the correction to the Ne-like level populations; therefore these Na-like ion states are accounted for in quasi-classical approach. Namely, each of 37 Ne-like levels corresponds to a Rydberg series of the autoionizing states of the Na-like ion: $2p^53l$ nl, $2s2p^63l$ nl. The series populations are described by the continuous functions of energy. Every Rydberg series is subdivided into three zones; therefore, we have 37 + 37×3 = 148 balance equations. All plasma elementary processes are accounted for which connect these two adjacent ions as well as processes of population redistribution between the zones and inside each zone. Reabsorption effects are accounted for every radiative transition by the Biberman-Holstein escape factor in the approximation [14]. We obtain the level population values by integrating the set of the balance equations with the definite initial conditions. Note that an important result of integration is an estimation of the timescale of Na-like ionization stage transformation to the Ne-like stage as a function of plasma parameters. The level widths due to all collisional processes in the Ne-like silver and those obtained by accounting for the multitude of Na-like states are listed in another work [15]. The motivation for the accounting for only two ionization stages is obvious. This approach allows one to judge the approximate conditions at which the Ne-like stage will appear. The time (τ) for the Na-like stage of ionization to change to the Ne-like stage is close to the total time of the Ne-like stage creation in the collisional-radiative model. In addition, the ionization balance calculation for these two ionization stages allows to scale the result for the more extended ionization balance which include the F-like stage.

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Table 2. Fraction of Ne-like ions [Ne] in a plasma containing the Ne-like and Na-like ionization stages: ([Ne]+[Na] = 1); population of the ground Ne-like state P(1), and the time need for the plasma to transform into a steady-state conditions τ (ps). Plasma thickness (d) depends on n_e

n_e(cm^{-3})	T_e (eV) →	1000	2000	3000	4000	5000
↓						
	[Ne]	0.25	0.59	0.74	0.82	0.86
$n_e=10^{21}$	P(1)	0.24	0.55	0.66	0.78	0.75
d=100μ	τ	140	76	53	38	33
	[Ne]	0.25	0.61	0.77	0.87	0.87
$n_e=5\times10^{21}$	P(1)	0.24	0.54	0.65	0.69	0.70
Fig.2						
d=30μ	τ	43	19	10.5	6.7	4.5
	[Ne]	0.25	0.61	0.77	0.87	0.88
$ne=10^{22}$	P(1)	0.23	0.52	0.62	0.69	0.67
d=20μ	τ	22	11	5.5	3.5	2.6
	[Ne]	0.24	0.62	0.76	0.83	0.88
$n_e=5\times10^{22}$	P(1)	0.20	0.39	0.42	0.47	0.45
d=5μ	τ	9.3	4.8	2.5	1.3	0.8
	[Ne]	0.25	0.65	0.76	0.83	0.87
$n_e=10^{23}$	P(1)	0.18	0.29	0.32	0.33	0.34
d=5μ	τ	2.5	0.9	0.5	0.3	0.2
	[Ne]	0.26	0.62	0.75	0.82	0.86
$n_e=5\times10^{23}$	P(1)	0.12	0.11	0.10	0.10	0.09
d=5μ	τ	0.7	0.3	0.15	0.08	0.04

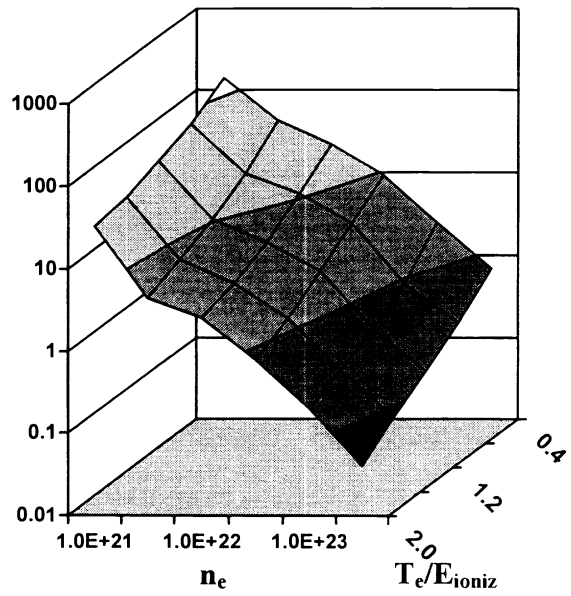


Fig. 2. **Time τ(ps) required for Na-like silver plasma to transform into the steady Ne-like state as a function of T_e/E_{ioniz} (0.4-2.0) and n_e (10^{21}-10^{24} cm^{-3}). Radiative-collisional approximation**

By solving the set of balance equations for the populations of the two ionization stages we find the population of every stage at any steady-state conditions. These results are shown in the Table 2. This table also gives the population of the Ne-like ion ground state and the time (τ) for the quasi-steady-state regime to be established. On Fig. 2 τ is shown for the ionization of Ag^{m+} to the next stage $Ag^{(m+1)+}$in silver plasma, as function of T_e/E_{ioniz} and n_e for $36 \le m \le 38$. One can see from Fig.2 that the time to reach a steady-state regime as well as the time of one stage to transform into another is roughly proportional to $1/n_e$ if $n_e \le 5\times10^{22}$ cm^{-3}. At electron temperature close to the ionization potential of Na-like ion the ionization balance shifts sharply to the Ne-like stage. Nevertheless at T_e exceeding the Na-like silver ionization energy, 20-14% of all ions remain in the Ne-like stage. This result shows that ionization and dielectronic recombination are almost balanced for these two ionization stages. This result also proves that the F-like stage appearance is impeded if $1 < T_e < 5$ keV (for Ne-like silver $E_{ioniz.} \approx 5.5$ keV).

Gain coefficients as functions of n_e, T_e are shown on Fig.3 a for the ordinary transitions discussed in the previous paper [7] and in the experiment [8]. Plasma diameter was chosen to be 100 μm for $n_e = 10^{21}$ cm^{-3}, and it decreased to d = 5 μm for $n_e > 5\times10^{22}$ cm^{-3}. The gain value is shown as degree of darkening. One can see from Fig.3a that optimum plasma parameters are different for 8-3 (2-1 transition at λ = 99.37 nm) and 23 -11 (another 2-1 at λ = 100.37 nm. For 8-3 transition the optimum value for density is in limits $10^{21} \le n_e \le 10^{22}$ cm^{-3}, whilst for 23-11 the optimum is: $5\times10^{22} \le n_e \le 10^{23}$ cm^{-3}. For the last transition at these n_e values and $4 < T_e < 5$ keV $g > 100$ cm^{-1}. The laser action at 2.75 nm is optimized at $n_e = 5\times10^{22}$ cm^{-3}. On Fig 3b gain coefficients are shown for selected transitions between highly excited levels. Only transitions are presented for which $g_{max} >$ 70 cm^{-1}. There are two basic reasons for strong laser action on these transitions: i) they are well populated at moderate T_e; ii) radiative transition probabilities from upper to the lower level are very strong (see Table 1). On Fig.4 a, b for all transitions the inversion $\Delta P = P_u - P_l(g_u/g_l)$ is shown versus n_e: a) for $T_e = 2$ keV; b) for $T_e = 5$ keV. For these two T_e values on Fig.5 a, b the gain coefficient dependencies on n_e are shown for the same transitions.

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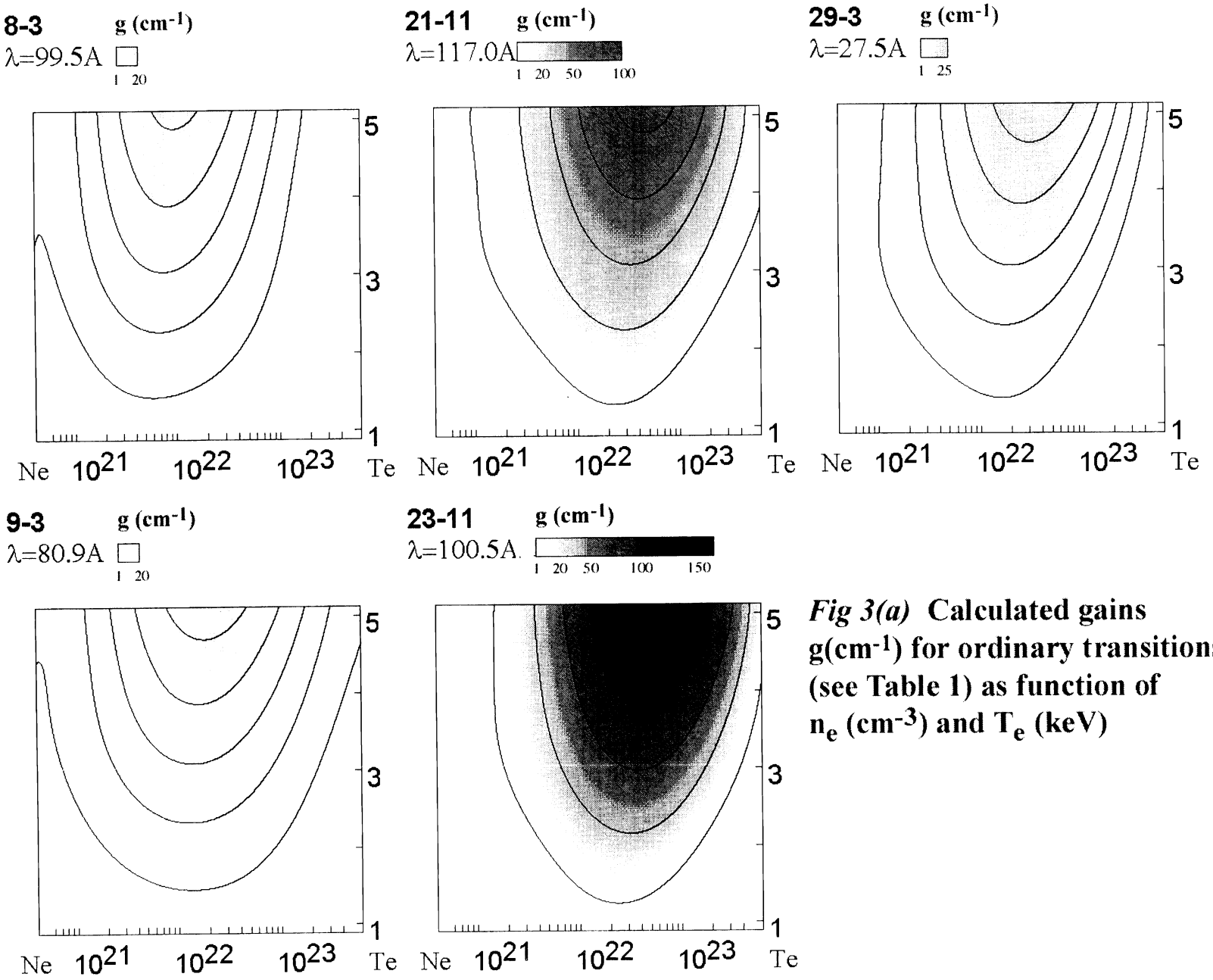


Fig 3(a) **Calculated gains $g(cm^{-1})$ for ordinary transitions (see Table 1) as function of n_e (cm^{-3}) and T_e (keV)**

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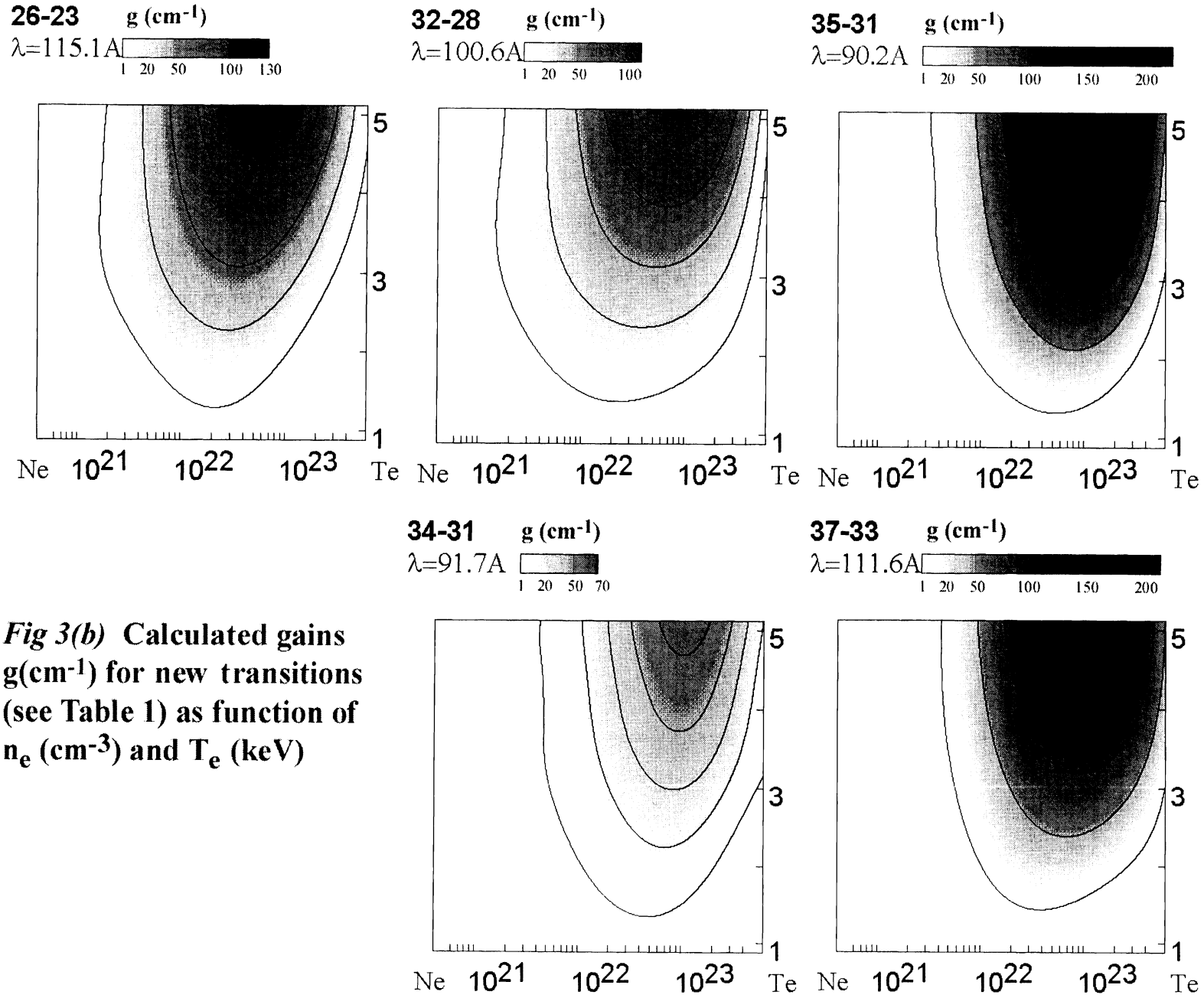


Fig 3(b) **Calculated gains g(cm^{-1}) for new transitions (see Table 1) as function of n_e (cm^{-3}) and T_e (keV)**

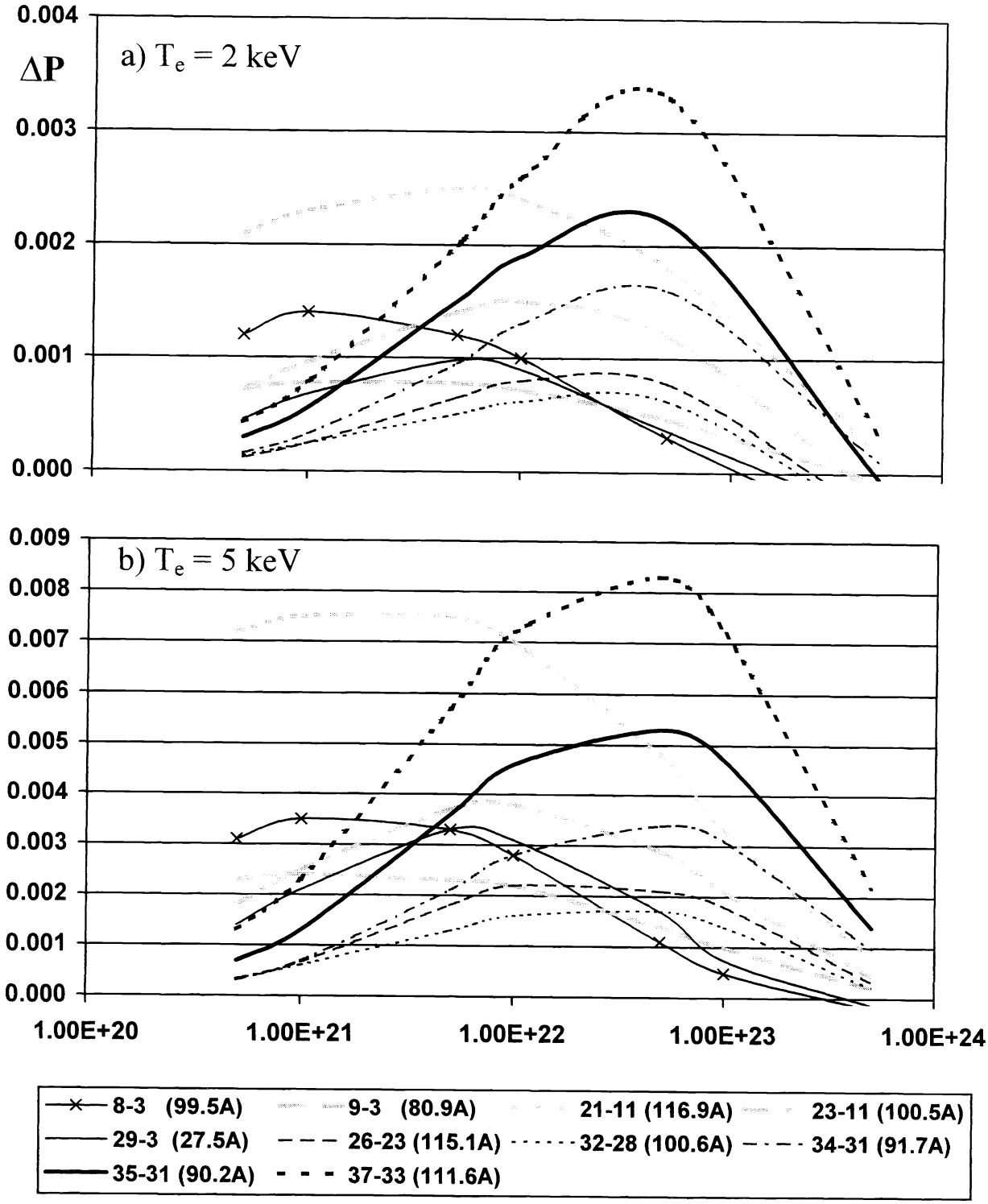


Fig. 4. **Population inversion $\Delta P = P_U - P_L \cdot g_u/g_l$ for selected transitions vs electron density n_e (cm^{-3}) in Ne-like Ag^{+37} plasma.**

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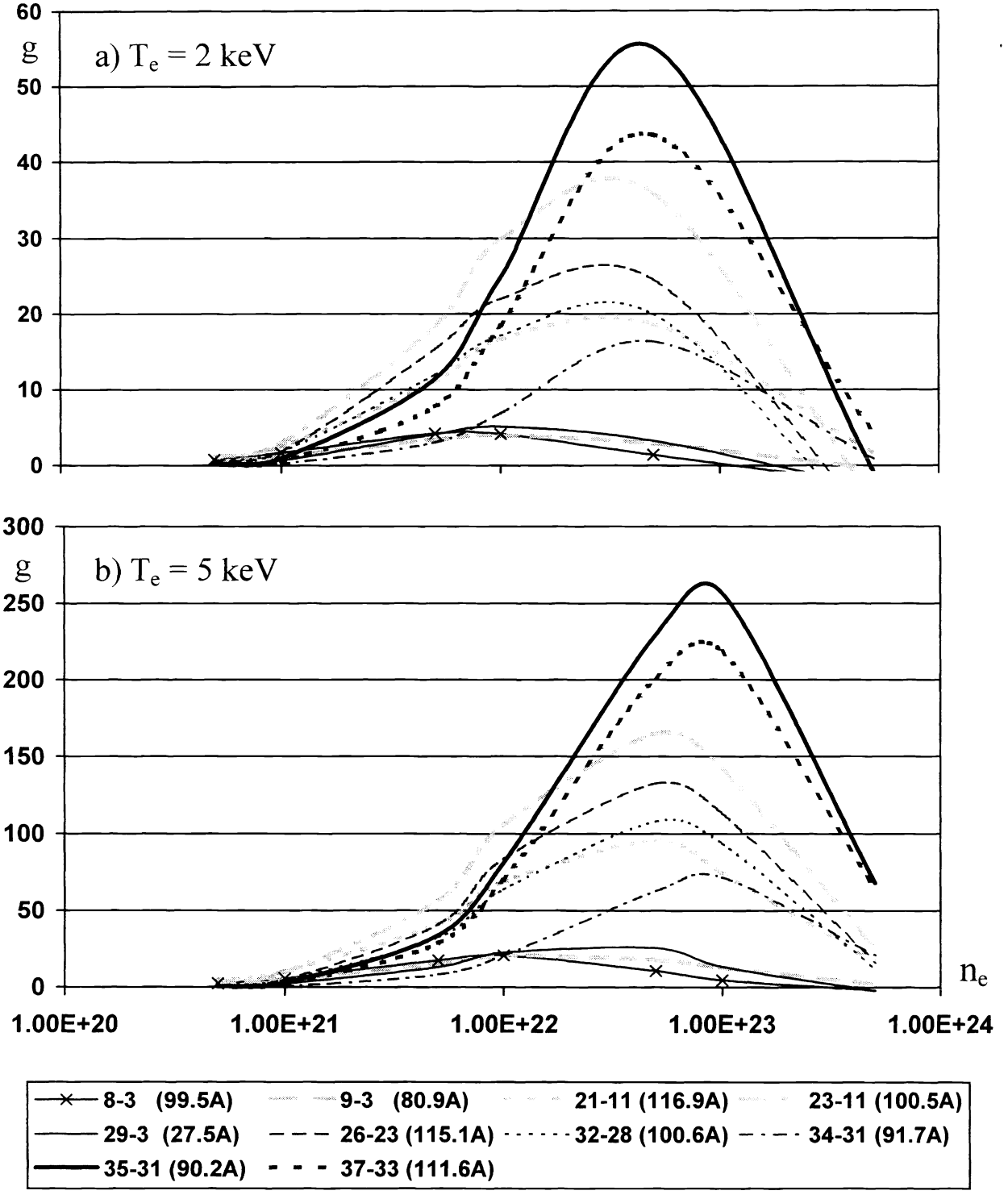


Fig. 5. **Gain g(cm^{-1}) for selected transitions vs electron density n_e (cm^{-3}) in Ne-like Ag^{+37} plasma.**

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CONCLUSION

The principle conclusion of present calculations is that the most effective lasing corresponds to the transitions between highly excited states of Ne-like silver at wavelengths: λ = 9.02 nm , λ = 9.17 nm, λ = 10.06 nm , λ = 11.16 nm, λ = 11.51 nm. For all other transitions of the bottom part of Table 1 maximum gain values exceed 20 cm^{-1} . Thus at $n_e > 10^{22}$ cm^{-3} there appear many new lasing channels in Ne-like silver plasma. The trustworthiness of the theoretical predictions is conditioned by the accuracy of radiative and collisional rate coefficient calculations, because inversion ΔP arises from a cancellation of two level populations which are of the same order in magnitude. Typically ΔP totals 10 - 30% of the upper level population; that implies the severe limitation for the accuracy of rate coefficients and level populations calculations.

It is important to understand the possible sources of error in the present calculations. A real plasma is never absolutely uniform and stationary. Thus this assumption will result in some error. If necessary, variation of the plasma parameters with space and time can be introduced. The electron energy distribution is unknown. We use the Maxwellian distribution; however we can change it for a two-hump Maxwellian or some other type of distribution. The ion temperature is approximated roughly by the electron temperature. That results in some error for Doppler and Voight line widths. Besides, only two ionization stages are included in the balance equations, thus unaccounted previous ionization stages are the source for some error in the ionization balance estimation. It should be noted that in a sufficiently dense plasma the interference between radiative and collisional decays can be large. Thus the study of plasma emission features demands a qualitatively different approach where an ion density matrix must be considered in dealing with the amplitudes for transitions between the ion states. We believe that the largest uncertainties in the final results are due to the fact that we have not accounted for the high electron configurations: $2p^5 4l$, $2s2p^6 4l$. In spite of this shortcomings this approximation allows us to predict the optimum plasma conditions for the onset of laser action and the optimization of the gain. As the short powerful pulse interacts with the target, the target burst , its thickness may be enlarged by a few microns; plasma stagnation time is determined by cooling , i.e. by plasma radiative loss. At the optimum plasma conditions plasma exists during 30-50 ps, because rate of radiative loss is ~1.5keV/(ps·ion), i.e. ~1% of the total kinetic energy per picosecond. For the silver target dimension 1cm $\times 20\mu m \times 0.2\mu m$ principal pulse energy is 100 - 200 J, FWHM = 1 ps, intensity $\geq 10^{17}$ W/cm^2.

Similar investigation was made in [16] for the selenium plasma. It was found [16] that highly non-equilibrium plasma conditions and a large gain coefficient > 500 cm^{-1} can be generated for the 0 -1 transition at 18.2 nm with KrF driving laser $I > 3\times 10^{16}$ W/cm^2 with 2 ps FWHM. Plasma parameters were calculated: T_e = 1030 eV, $n_e = 1.8\times 10^{22}$ cm^{-3}. Under these conditions selenium plasma ionizes beyond the Ne-like ionization stage on a 10 ps time scale. In this case the gain is transient as it acquires nonzero values on a 5.5 ps timescale. Thus the target length should be of the order of millimeter. In contrast to selenium plasma the Ne-like stage in silver plasma is non-transient at T_e close to the ionization potential of the Ag^{37+}. The reason is that for this ion charge all processes of ionization are quasi-balanced with the processes of electron recombination; thus, at this T_e the ionization balance for Ag^{37+} is stable.

As a result of this study we conclude that large inversion values are possible in the Ne-like state of a dense hot silver plasma. The Ne-like state and inversion are of steady-state (non-transient) character. The necessary plasma conditions can be obtained with a high-contrast, high-intensity short-drive-laser pulse with a properly designed target. That can result in high gain laser medium. This approach has distinct advantages:

(a) A significant increase in the gain values.
(b) Arising of additional lasing channels.
(c) A laser output at a shorter wavelength at λ = 2.75 nm.
(d) An increase in the brightness of x-ray laser beam .
(e) An improvement in plasma uniformity.
(f) An increase in the conversion of the input energy to the output laser radiation.

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