Investigation of population inversion in Al III for amplified spontaneous emission at 170 Å

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Several $2p^5(3s3p\,^3P)^2P$, ^2D core-excited levels of Al III appear to have large radiative branching ratios to $2p^6\,3p\,^2P$. We propose to produce a population inversion between these levels and amplified spontaneous emission at $\lambda \approx 170$ Å by photoionizing the Al II $2p^6\,3s3p\,^3P$ metastable levels with the N-shell quasicontinuum band of Sb around 125 Å. By pumping with the Sb band, the secondary electron heating of the lasing medium is minimized, which enables a fast collisional depletion of the $2p^6\,3p\,^2P$ levels and a longer-lived inversion. A model of the population kinetics in this scheme indicates that by irradiating a dense and cold Al II plasma ($N_e \approx 3\times10^{17}$ cm^{-3}, $T_e \approx 1.2$ eV) with a Sb quasicontinuum pulse of 100–150 ps FWHM and $5\times10^9-10^{10}$ W/cm^2 peak intensity, gain coefficients between 1 and 3 cm^{-1} for a duration of 100–150 ps may be obtained. The target parameters are typical for stabilized arc plasmas. The possible extrapolation of this inversion scheme to shorter wavelengths and the use of neutral targets are briefly discussed.

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I. INTRODUCTION

Some of the $2p^5nln'l'$ core-excited levels of light Na-like ions may be metastable against autoionization and therefore of interest for population inversion in the soft x-ray and far ultraviolet (XUV) range [1,2]. The atomic physics underlying their metastability has been discussed recently by Gaarstedt and Andersen [3]. Two types of inversion schemes based on such levels have been proposed: In the first one, Mg I atoms are preexcited with a tunable UV laser in the $2p^6\,3s3p\,^1P_1$ level and then photoionized with soft x-ray radiation to populate the $2p^5(3s3p\,^1P)$ levels of Mg II [1]. Of these, $2p^5(3s3p\,^1P)\,^2P_{3/2}$ has been predicted to have a large radiative transition probability to $2p^6\,3p\,^2P_{3/2}$, leading eventually to amplified spontaneous emission (ASE) at 236 Å. In a second scheme, the quasimetastable or metastable $2p^5\,3s3p$ quartet levels of Na I or Mg II are used as storage levels [2]. From these, population is to be transferred by optical pumping into one of the $2p^5\,3s3d$ or $2p^5\,3s4s$ levels which have large radiative branching ratios to $2p^6\,3d$ or $2p^6\,4s$, respectively. To ensure population inversion, it has been proposed also to deplete the lower laser levels by photoionization or photoexcitation into nearby levels with an additional tunable laser.

Besides being difficult from an experimental point of view, none of the above schemes can be extrapolated easily to shorter wavelengths. The first one cannot be applied because in ions higher than Mg II in the Na I sequence the $2p^5(3s3p\,^1P)\,^2P_{3/2}$ level appears to be severely mixed with rapidly autoionizing levels [4,5]. For the second scheme the possible transfer transitions fall in the extreme ultraviolet (EUV) range [6]. However, our recent experimental and theoretical results seem to indicate that compared to the previous ions, the $2p^5(3s3p\,^3P)$ manifold in Al III undergoes a significant stabilization against autoionization [4]. This may give rise to new soft x-ray lasing schemes. Several $2p^6\,3p\,^2P$-$2p^5(3s3p\,^3P)\,^2P,^2D$ Al III transitions around 170 Å appear to have large radiative branching ratios and gain cross sections above 10^{-15} cm^2. We propose therefore an Al II–Al III inversion scheme in which the upper levels of these transitions are populated by inner-shell photoionization of a dense Al II plasma having a large fraction of $2p^6\,3s3p\,^3P$ metastable ions. In the present work we consider using a narrow band of soft x-ray continuum with energy above the $2p$ inner-shell ionization threshold for photopumping. Such bands of quasicontinua are produced by the overlap of a very large number of 4-4 transitions of the N-shell ionized atoms for elements with $Z > 50$ [7,8]. Results of modeling the population kinetics in this scheme are presented.

Section II presents the principle of the scheme and evaluates the possible target plasmas. Section III describes the time-dependent collisional radiative model used to predict the Al III level populations; Section IV presents results of modeling the photoionization of an Al II plasma. In Sec. V we discuss briefly the possible extrapolation of the scheme to shorter wavelengths and the use of a neutral Al I target.

II. THE Al II–Al III LASING SCHEME

The proposed population inversion scheme is depicted in the diagram below (see Fig. 1). The basic issues regarding inner-shell photopumped schemes are discussed by Elton [9]. A significant simplification in our proposed scheme is that the Al II $2p^6\,3s3p\,^3P$ reservoir levels are strongly populated by electron collisions in the lasing plasma. Due to their metastability, large statistical weight, and proximity to the ground level ($\Delta E = 4.65$ eV), these levels easily may accumulate populations comparable to that of the ground level. As we will show below, electron collisions may play other useful roles in this scheme.

In the proposed scheme, one is interested in the population inversion of the $2p^5(3s3p\,^3P)\,^2P,^2D$ levels, which decay radiatively to $2p^6\,3p\,^2P$ at rates of about 5×10^9

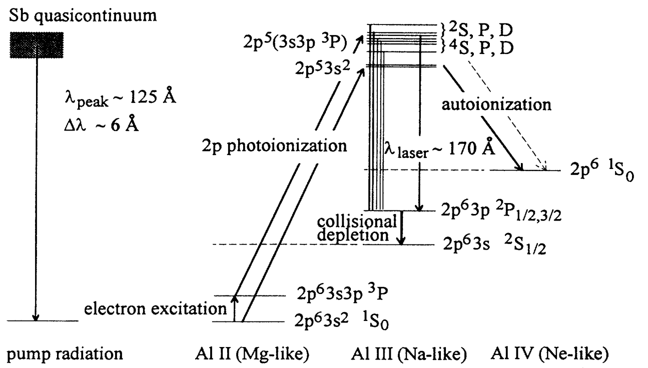

FIG. 1. Diagram of the quasicontinuum photopumped Al II–Al III lasing scheme.

s^{-1}. Thus for ASE they require upper level populations that are not too high ($\approx 10^{15}$ cm^{-3}) [4]. On the other hand, the transitions connecting the $2p^6 3p$ lower laser levels to the ground have smaller radiative rates ($\approx 5\times 10^8$ s^{-1}). If radiative decay were the only mechanism for depleting these lower levels, the radiative decay from $2p^5(3s3p\ ^3P)$ would fill them in a few tens of ps and the inversion would be extremely short lived. We observe, however, that in a dense lasing plasma, deexcitation collisions with cold electrons may deplete the $2p^6 3p$ levels faster than they are populated by the radiative cascading. Using Al III collision strengths calculated in the close-coupling approximation [10] we obtain for example at $T_e = 1.5$ eV and $N_e = 3\times 10^{17}$ cm^{-3} a total $2p^6 3p \rightarrow 2p^6 3s$ collisional deexcitation rate of approximately 10^{11} s^{-1}. This is significantly larger than any $2p^5(3s3p\ ^3P)\,^2P,\ ^2D \rightarrow 2p^6 3p\ ^2P$ radiative decay rate [4].

Of course electron collisions will also populate the $2p^6 3p$ levels by excitation of the Al III ions in the ground level ($\Delta E_{3s\text{-}3p} = 6.67$ eV). However, from the detailed balance principle, in plasma conditions as stated above the $3s \rightarrow 3p$ excitation rate is only $\approx \frac{1}{30}$ of the deexcitation rate. In addition, the collisional depopulation is much less significant for the $2p^5(3s3p\ ^3P)\,^2P,\ ^2D$ upper laser levels: At the above plasma parameters we estimate for the $^2D_{5/2}$ level, for example, a total deexcitation rate to the $2p^6 3l$ ($l = s$, p, and d) and $2p^5 3s^2$ levels of only 5×10^8 s^{-1}. Thus, as long as the concentration of ground-state Al III ions and the electron temperature in the lasing plasma are sufficiently low, it is possible in principle to maintain population inversion for any $2p^6 3p\ ^2P$-$2p^5(3s3p\ ^3P)^2P,\ ^2D$ transition.

The electrons of the lasing plasma are heated mainly by collisions with the energetic secondary electrons produced by inner-shell photoionization ($2p$ photoelectrons or Auger electrons emitted in autoionization decays). The heating by Auger electrons is unavoidable. Although the $2p^5(3s3p\ ^3P)$ levels of Al III appear to decay predominantly by photon emission, the $2p^5 3s^2$ levels, which are also populated by the pump radiation from the initially abundant Al II ground state, have autoionization yields close to one with rates around 10^{11} s^{-1} [4]. Thus one may expect that an intense pulse of Auger electrons having an energy around the $2p^6$-$2p^5 3s^2$ transition energy of ≈ 45 eV will accompany the pulse of pump photons.

The photoelectron heating, however, may be eliminated by a careful choice of the pump spectrum. By pumping with radiation tuned just above the $2p$ threshold the photoelectrons will be ejected with negligible kinetic energy. The line radiation must be excluded for such purposes due to the limited photon flux available in a single transition. One may consider, however, the use of narrow bands of soft x-ray continua with $\Delta\lambda/\lambda \approx \frac{1}{20}$. In principle such bands could be produced from a broad soft x-ray continuum by selective absorption [11]. However, this is experimentally difficult and may convert a good part of the absorbed soft x-ray radiation into unwanted, low-energy photons.

Instead we propose to achieve the narrow-band pumping required in the Al II–Al III scheme, using atomic bands of continuum produced directly by the pump plasma. Such band are the heavy element N-shell quasicontinua mentioned above. In our case the suitable element is Sb ($Z = 51$), which produces a band centered at $\lambda \approx 125$ Å and having $\Delta\lambda \approx 6$ Å [7]. The possibility of achieving in such bands the brightness required for optical pumping has been demonstrated for elements with $Z = 79$–82, which emit at wavelengths around 40 Å [12]. At lower Z and longer wavelengths this problem has not been yet studied. However since the N-shell quasicontinua are composed mainly of overlapping $4d$-$4f$ resonance transitions [8], we assume that in suitable excitation conditions the Sb band at 125 Å can also be produced with high brightness.

The Al II target plasma has to be as cold and as dense as possible. As discussed above these conditions favor collisional deexcitation of the lower laser levels. Also, a high-density medium can compensate for the relatively low photon flux available in a narrow continuum band. However a dense plasma cannot be arbitrarily cold, the limiting situation being when its Coulomb correlation energy becomes comparable to its thermal energy [13]. To give practical meaning to our computations, we assumed initial target parameters in the range typical for high power, wall stabilized arcs. Experiments have shown that densities around 10^{17} cm^{-3} at 1 eV, and up to about 10^{18} cm^{-3} at 1.5 eV, may be achieved in metal-vapor arcs [14]. Also, such arcs have been observed to fulfill local thermodynamic equilibrium (LTE) conditions quite closely [14]. Thus one may easily estimate that due to the high ionization potential of Al II (18.8 eV), an Al arc at a temperature of 1–1.5 eV will produce a nearly pure Al II plasma.

We note that dense Al II plasma may be also produced by low power laser irradiation of Al targets. Costello and Evans [15] have measured significant soft x-ray absorption for such plasmas consistent with densities in the above range.

III. MODEL FOR GAIN ESTIMATES

A. Levels and processes included in the model

In the Al II–Al III scheme modeling we consider the Al II ground and $2p^6 3s3p\ ^{1,3}P$ levels, all the Al III

$2p^6 3l (l = s, p,$ and $d)$ and $2p^5 3s 3l (l = s,$ and $p)$ levels, and the Al IV ground. The Al II $2p^6 3s 3p\ ^3P$ term is treated as a single level of statistical weight 9. As we discussed earlier [4], this is a fair assumption even at low density since the $J = 0$, 1, and 2 levels are separated by less than 20 meV. We also neglect the Al II configurations higher than $2p^6 3s 3p$ or the Al III configurations above $2p^5 3s 3p$. This is because the respective energy gaps are of at least 7–8 eV [6], while under the conditions of photopumping assumed here the temperature of the lasing medium will remain below 2–3 eV. Therefore, the higher-lying levels are not expected to be populated strongly or to affect significantly the kinetics of the inversion.

Regarding the photon-induced processes, the model includes inner-shell and outer-shell photoionizations for the Al II ion and outer-shell photoionization for Al III. Stimulated emission is not included in the rate equations because a relatively low gain coefficient is anticipated. Also, the absorption of the quasicontinuum photons by inverse bremsstrahlung is neglected, since this process has a much lower cross section than $2p$ photoionization.

The pump spectrum is assumed to be a band of constant intensity between 120 and 130 Å. The photon density in the lasing medium is assumed to be spatially uniform, but time dependent. The temporal profile of the pump pulse is assumed to be Gaussian, with a temporal width (FWHM) in the range of 100–500 ps. The irradiance of the Al II target at the peak of the quasicontinuum pulse is taken as 5×10^9 W/cm^2. This quite low value suffices for ASE, due to the relatively long lifetime of most the $2p^5(3s3p\ ^3P)$ levels [4], and the high density assumed for the Al II target. Assuming a photon coupling in which about $\frac{1}{4}$ of the pump photons reach the target, this irradiance would require a pump modal density of about 0.05 photons/mode [9].

The electron-induced processes considered are excitation, deexcitation, and ionization involving the bulk plasma electrons and the Auger electrons, as well as three-body recombination involving the bulk electrons. The collisional transitions between the Al III levels, expected to play a determining role for inversion, are treated in details. The population of the Al II $2p^6 3s 3p$ metastable levels is treated, however, in a simplified manner, as are ionization and three-body recombination involving Al II and Al III ions and the bulk electrons. The approximations will be discussed below.

The spontaneous decay processes included are radiative decay and autoionization for all the $2p^5(3s3p\ ^3P)$ levels. The radiative decay of the $2p^6 3p$ lower laser levels has been neglected since, as discussed above, collisional deexcitation is faster by orders of magnitude. In addition, at the ionic densities considered here the $3s$-$3p$ transitions are severely trapped.

The bulk electrons are assumed to be Maxwellian, since in the dense and cold plasmas we considered the electron-electron energy equipartition time is a few ps. The Auger electrons are considered monoenergetic with an energy $E_A = 45$ eV. The slow $2p$ photoelectrons have been neglected. The density of Auger electrons in the lasing medium $N_A(t)$ is obtained with the approximation

$$\frac{dN_A(t)}{dt} \approx \sum_k N_k(t) A_k^a - N_A(t) \sum_i \frac{\Delta E_i}{E_A} \frac{1}{\tau_i(t)} , \quad (1)$$

where N_k and A_k^a are the population and autoionization rate of autoionizing level k, and $\Delta E_i / E_A \tau_i(t)$ is the energy loss rate via collisional process i, having an energy loss per collision ΔE_i and a characteristic time τ_i. A similar approximation has been used by Caro in the description of secondary-electron thermalization in photoelectron-produced plasmas and found to give reasonable results [16]. The thermalization processes considered are Coulomb collisions with the bulk plasma electrons, and excitation or ionization of the outer-shell electrons of Al II and Al III ions. The characteristic time for thermalization by Coulomb collisions of monoenergetic electrons of velocity v_A in a cold plasma of density N_e is $\tau_C \approx 6\times10^{-20} v_A^3 / N_e$ [13]. This leads, at the densities considered here, to thermalization times of a few tens of ps for the Al III Auger electrons.

The characteristic times for ionization and excitation collisions are taken as

$$\tau_i(t) \approx \frac{1}{N_i(t) v_A \sigma_i(v_A)} , \quad (2)$$

where N_i is the populations in the ground states of Al II and Al III or in the Al II metastable levels, and σ_i the ionization or excitation cross sections of the resonance transitions of these ions. The largest contribution arises from optically permitted excitation collisions which have cross sections around 5×10^{-16} cm^2, leading to thermalization times similar to that due to Coulomb collisions.

The evolution of the electron temperature in the lasing medium is obtained from the energy balance

$$\tfrac{3}{2} N_e(t) \frac{dT_e(t)}{dt} \approx \frac{N_A(t) E_A}{\tau_C} - W_{\text{ion}}(t) . \quad (3)$$

The first term represents the energy transferred per unit time and volume by the Auger electrons to the bulk electrons via Coulomb collisions, while W_{ion} denotes the energy lost per unit time and volume in outer-shell ionization events. The radiative cooling of the plasma is neglected since we assume that the vacuum ultraviolet (vuv) radiation emitted by Al II and Al III is almost completely trapped. Also neglected is the heating of the bulk electrons in three-body recombination events, since we assume the plasma to be in a dominantly ionizing phase during the photon pulse.

B. Approximations in the treatment of the Al II ion

To avoid the addition of a very large number of Al II excited levels to our model, we made a series of simplifying assumptions. The first is to consider that the population of the $2p^6 3s3p\ ^3P$ metastable term is in Boltzmann equilibrium with respect to the ground population. The validity of this assumption may be examined by comparing the $2p^6 3s^2\ ^1S_0 \rightarrow 2p^6 3s3p\ ^3P$ collisional excitation times with the time scale of the photopumping of a few hundred ps. Using R-matrix collision strengths for Al II

[17], we estimate a characteristic time of ≈ 80 ps at $N_e = 3\times 10^{17}$ cm^{-3} and $T_e = 1.5$ eV for the equilibration of the ground and metastable populations. The assumption of Boltzmann equilibrium is, therefore, moderately good.

A more difficult problem has been to estimate in a simple manner the ionization rate of Al II ions by the Maxwellian electrons. Although ionization from the ground and $3s3p$ levels has been treated exactly, at the densities of interest here ionization by the bulk electrons proceeds predominantly through ladder excitations followed by ionization from high-lying levels [18]. To account for these processes we introduced a temperature- and density-dependent effective ionization rate coefficient $S_{\rm eff}(N_e, T_e)$, similar to the collisional-radiative ionization coefficients introduced in a quasi-steady-state model by McWhirter [19]. As discussed recently by Fujimoto and McWhirter [18], for nonhydrogenlike ions in fast ionizing plasmas as is the case here, hydrogenlike approximations may be quite crude. Therefore, we tried to account for the particular level structure of Al II, using an approach proposed by Hinnov and Hirschberg [20]. In this method, accurately calculated ionization rates from excited levels are introduced for levels up to a critical level, for which the upward and downward transition rates are equal. In the present work the following effective ionization coefficient has been introduced:

$$S_{\rm eff}(N_e,T_e)\approx S_g + S_{3s3p} + \mathcal{S}_{gg'}(T_e) g_{g'}/g_g b(N_e/N_{\rm LTE}) \sum_n^{n^*} \beta_n \ , \qquad (4)$$

where S_g and S_{3s3p} represent the calculated ionization rate coefficients for the ground state and for all the $3s3p$ levels. $\mathcal{S}_{gg'}(T_e) = 6\times 10^{21} T_e^{1.5} \exp(-\chi/T_e)$ cm^{-3} is the Saha-Boltzmann coefficient (χ being the ionization potential of Al II) and g_g and $g_{g'}$ are statistical weights of the ground states of Al II and Al III. $N_{\rm LTE}$ is the critical electron density required for local thermodynamic equilibrium in the Al II level populations, and the coefficient $b(N_e/N_{\rm LTE})$, which we have approximated as $\tanh(N_e/N_{\rm LTE})$, has been introduced to describe the transition from coronal equilibrium ($b \approx 0$) to complete LTE ($b\approx 1$) [19]. n labels all the higher excited levels up to the critical level n^*, and β_n represents the three-body recombination rate coefficient into level n.

The advantage of this form is that it enables a simple evaluation of the terms to be kept in the sum over β_n. Indeed, as noted by Hinnov and Hirschberg [20], at high electron density the effective three-body recombination rate includes only recombinations into those levels for which the higher probability is collisional deexcitation toward low levels. In this way, using computed ionization [21] and excitation [17] cross sections, we have determined the Al II critical level as a function of temperature and obtained a total three-body recombination coefficient from Al III to Al II, which can be described by an approximate analytical form:

$$\sum_n^{n^*(T_e)} \beta_n \approx 4.5\times 10^{-27} T_e^{-3} \ [\text{cm}^6/\text{s}] \ . \qquad (5)$$

At low temperatures this is comparable with that derived for hydrogen [20]. Finally, $S_{\rm eff}(N_e, T_e)$ is deduced from relations (4) and (5).

Our estimate for $S_{\rm eff}(N_e,T_e)$ indicates that during the second half of the quasicontinuum pulse the rate of ionization of Al II by thermal electrons becomes comparable to the rate of inner-shell photoionization and has, therefore, a significant role in the termination of the inversion. A similar procedure has been used to estimate the effective ionization and recombination rate coefficients for the Al III ion. In this case, however, due to the lack of metastable levels and to the higher ionization potential of Al III, the ionization is dominated by fast electron collisions with ground-state ions.

C. Line broadening mechanisms

The gain varies as the inverse of the width of the lasing transition [9]. Regarding Doppler broadening, it is assumed that the ionic temperature is at all times around one third of the electron temperature, as it is generally in arcs. This may be an overestimate, since the electron-ion energy equipartition time (several ns) is very long compared to the electron temperature rise time of a few hundred ps.

In the present case the lasing medium is cold and dense and collisional Stark broadening may play a greater role than the Doppler effect. Stark broadening has been estimated using earlier studies. As pointed out by McCorkle and Joyce [22], the dominant broadening mechanism for core-excited levels like $2p^5 3s3p$ is the quadratic Stark effect due to ion collisions. (The linear Stark effect is not significant due to the shielding of the core from the plasma by the outer-shell electrons.) Computing this contribution using the formula in Ref. [22], one obtained a negligible width of several GHz for the upper levels. Thus the dominant contribution to the widths of the $2p^6 3p$-$2p^5 3s3p$ transitions arises from electron-impact broadening of the lower levels. The broadening of $2p^6 3p\ ^2P$ has been obtained by scaling the widths measured for the $3s$-$3p$ transitions of Mg II in arc plasmas [23] to Al III. The combined Doppler and Stark widths give the following total width:

$$\Delta\omega \approx \Delta\omega_D + \Delta\omega_S \approx 900(T_e/3)^{1/2} + 100 T_e^{-1/2}(N_e/10^{17}) \ , \qquad (6)$$

where $\Delta\omega$ is in units of GHz, T_e in eV and N_e in cm^{-3}. Thus, at densities above 7×10^{17} cm^{-3} and for T_e around 1.5 eV, Stark broadening becomes dominant for the lasing transitions.

D. Atomic data

The Al III autoionizing level energies, radiative and autoionization decay rates, and excitation collision strengths (computed in the distorted-wave approximation) used in the model have been presented in a recent work [4]. The distorted-wave (DW) collision strengths for the transitions among the $2p^6 3l$ ($l = s$, p, and d) Al III levels are replaced in the present work by collision strengths computed with the close-coupling (CC) method [10]. As discussed above, in the scheme we propose, the collisions involving these levels are critical for inversion. It is therefore important to describe these collisions as accurately as possible. By including the effect of resonances in the excitation cross sections the CC method is able to reproduce within about 10% the experimental data for Al III [10].

The accuracy is probably lower for the transitions involving the $2p^5\,3s^2$ and $2p^5\,3s3p$ configurations, for which only DW collision strengths were available [4]. As most of these transitions are optically forbidden, it may be inferred that at the low temperatures considered here the DW data underestimate the collisional rate coefficients, since they do not account for the low-energy resonances in the excitation cross sections. The only comparison possible is with recent close-coupling computations for the optically forbidden transitions within the $2p^5\,3s3p$ configuration of Na I [24]. The authors predict, for example, that the collision strengths for the $2p^5\,3s3p\,{}^4S$-$2p^5\,3s3p\,{}^4D$ optically forbidden transitions are comparable with those for the $2p^6\,3s\,{}^2S$-$2p^6\,3d\,{}^2D$ transitions. In our Al III data, the corresponding $2p^5\,3s3p\,{}^4S$-${}^4D$ distorted-wave collision strengths are smaller by a factor of 1.4 than the close-coupling $2p^6\,3s$-$2p^6\,3d$ ones [10]. We infer, thus, that our distorted-wave data may underestimate by this factor the collision strengths within the $2p^5\,3s3p$ manifold. However, the above difference could be due to a decrease in the resonance contribution, which scales as the inverse of the ionic charge.

The Al II and Al III photoionization cross sections have been obtained from the recent data compilation of Verner *et al.* [25], and the electron-impact ionization cross sections were taken from the work of Arnaud and Rothenflug [21]. The partial cross sections for photoionization from $2p^6\,3s3l$ ($l=s$ and p) levels into one of the $2p^5\,3s3l$ levels may be obtained assuming statistical branching coefficients [4].

The system of differential rate equations of the model has been integrated using an adaptive step algorithm in which the rate coefficients have been recalculated at each step. The time step required for 1% accuracy of the solution is around 0.2 ps.

IV. RESULTS AND DISCUSSION

Figures 2(a) and 2(b) present the time dependence of the reduced population (N_k/g_k) of Al III levels of interest for lasing and the corresponding gain coefficients. For clarity only the $2p^6\,3p\,{}^2P_{3/2}$ lower laser level and the $2p^5(3s3p\,{}^3P)\,{}^2D_{5/2}$ and ${}^4D_{5/2}$ autoionizing levels, which lead to the largest gain among the doublets and quartets, are presented. The parameters of the photon pulse in these computations are 150-ps temporal width (FWHM) and peak irradiance of 5×10^9 W/cm^2. The initial parameters of the Al II target plasma are $N_{e_0}\approx N_{\mathrm{Al\,II}_0}=3\times10^{17}$ cm^{-3} and $T_{e_0}=1.2$ eV.

Figure 3 shows the dependence of the peak gain and duration of inversion on the initial target parameters for the above photon pulse. As discussed in Sec. II, we assume that the higher the initial density N_{e_0} of the target plasma, the higher must be its initial electron temperature T_{e_0}. From the typical values of arc plasmas [14] we derived an approximate dependence: $T_{e_0}\approx0.4[\log_{10}(N_{e_0})-14.5]$. Thus in Fig. 3 T_{e_0} varies according to this relation.

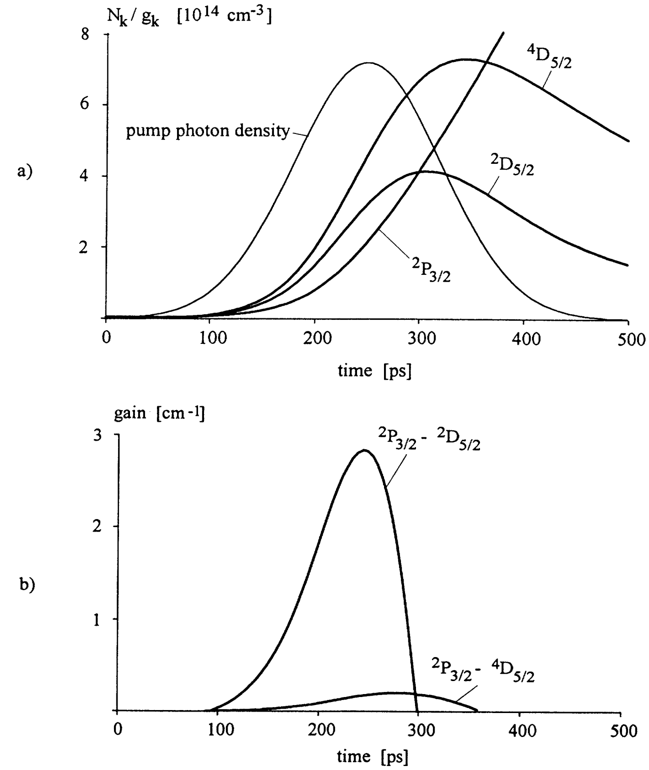

FIG. 2. Reduced population of the upper and lower levels of the lasing transitions (a) and gain (b) for a $N_{e_0}=3\times10^{17}$ cm^{-3}, $T_{e_0}=1.2$ eV Al II plasma, pumped by a 150-ps Sb quasicontinuum pulse of 5×10^9-W/cm^2 peak irradiance. ${}^4D_{5/2}$ and ${}^2D_{5/2}$ represent the $2p^5(3s3p\,{}^3P)\,{}^4D_{5/2}$ and ${}^2D_{5/2}$ upper levels, and ${}^2P_{3/2}$ denotes the $2p^6\,3p\,{}^2P_{3/2}$ lower level. The time scale zero corresponds to the beginning of the pump pulse. (The pump photon density is not shown to scale.).

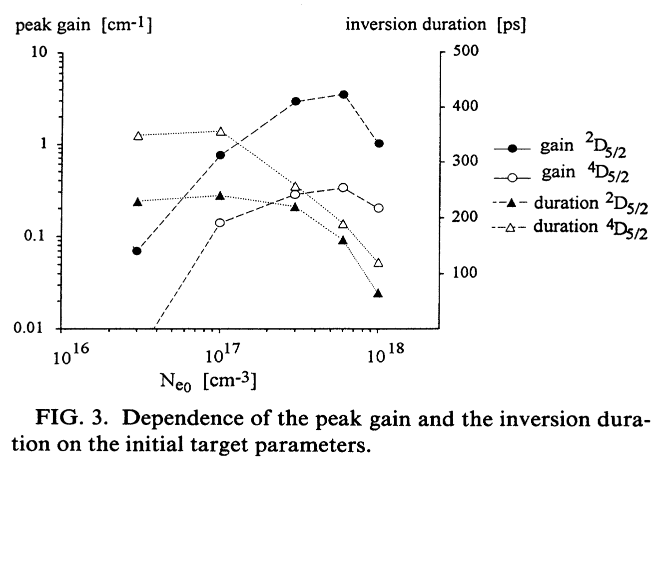

FIG. 3. Dependence of the peak gain and the inversion duration on the initial target parameters.

The results indicate that for a relatively large range of initial target parameters, a population inversion with respect to the $2p^6 3p$ levels can be obtained for most of the $2p^5 3s3p$ quartets and some of the fast radiating doublets. The upper-level populations increase with initial target density. At $N_{e_0} \approx 3 \times 10^{17}$ cm^{-3} and $T_{e_0} \approx 1.2$ eV the gain is sufficient for significant ASE for the $2p^6 3p\ ^2P_{3/2}$-$2p^5(3s3p\ ^3P)\ ^2D_{5/2}$ transition at 170 Å. The gain for the transitions from $2p^5(3s3p\ ^3P)\ ^2D_{3/2}$ or $^2P_{3/2}$ upper levels is about half that for the 170-Å line. Above $N_{e_0} \approx 10^{18}$ cm^{-3} and $T_{e_0} \approx 1.5$ eV inversion is no longer achieved due to the initial large fraction of Al III ions in the $2p^6 3p$ levels. As shown in Fig. 2(b), the duration of significant gain (> 1 cm^{-1}) for the doublet-doublet transition is limited to about 150 ps. The gain for the doublet-quartet is longer lived, but too low for significant ASE.

Since the termination of the inversion is due to the fact that the $2p^6 3p$ population increases faster than that in the upper laser levels, increasing the length of photon pulse does not prolong the inversion. Shortening it to 50–70 ps, on the other hand, decreases the gain and the duration of the inversion only slightly. As indicated in Sec. II and illustrated in Fig. 2(a), the inversion lasts for about 200 ps, significantly longer than the predicted characteristic time (few tens of ps) for inversion cancellation by the radiative decay to the lower levels. This can be explained by the role of collisional depletion of the lower levels. The population and depletion rates for the $2p^6 3p$ levels are presented in Fig. 4. This figure shows that collisional depletion is at all times intense enough to counterbalance the radiative and collisional decay from all the upper $2p^5 3s3p$ levels and also the ionization from Al II levels (the plasma parameters are the same as in Fig. 2). Moreover, in the first few hundred ps collisional depletion of $2p^6 3p$ is also more intense than collisional excitation from the ground, enabling a longer-lived inversion.

The rapid increase in the $2p^6 3p$ populations is due mainly to the heating of the lasing medium by the Auger electrons emitted in $2p^5 3s^2 \rightarrow 2p^6$ autoionization. Since their thermalization time scales as $\approx 1/N_e$ (N_e being the bulk electron density) and their production rate as $\approx N_e$, the rate of electron temperature increase is less influenced by the parameters of the lasing plasma, but is mostly determined by the rise time and intensity of the photon pulse, and by the autoionization branching ratio for the $2p^5 3s^2$ configuration.

However, the Auger electron heating also has the beneficial effect of increasing the Al II metastable state population. As illustrated in Fig. 5, the population of Al II metastable states reaches a maximum approximately at the peak of the pulse, even though the overall population of Al II ions is depleted by photon and electron ionization. The nonequilibrium population distribution observed between Al III and Al IV is due to Auger decay and lasts several ns after the photon pulse.

Regarding the autoionizing levels, the collisional mixing within the $2p^5(3s3p\ ^3P)$ manifold has the effect of increasing the population in the doublet levels involved in ASE at the expense of the quartet populations. This is illustrated in Fig. 6, which shows the population of these levels, obtained with and without collisional mixing. At the initial density considered ($N_{e_0} \approx 3 \times 10^{17}$ cm^{-3}), the decay rates of all the autoionizing levels are brought by collisions to a common rate of about 5×10^9 s^{-1}. This enhances the populations of the $2p^5(3s3p\ ^3P)$ doublets for which the sum of the radiative and autoionization rates are larger than this collisional averaged decay rate. However, this effect takes place relatively late, due to the time needed for building up the population of the $2p^5(3s3p\ ^3P)$ quartets. Since at late times the lower-level populations are also built up to very large values, the collisional mixing does not help much to prolong the inversion.

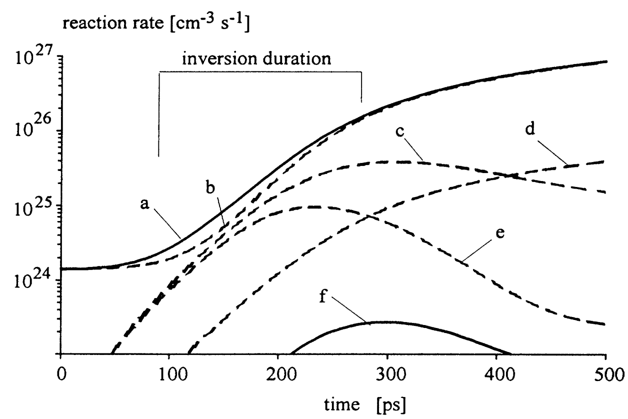

FIG. 4. Reaction rates for the main processes of population and depopulation of the $2p^6 3p\ ^2P$ lower laser levels (plasma parameters are the same as in Fig. 2): (a) Depletion by deexcitation of Al III ground or excitation to $2p^6 3d$ levels in collisions with cold, bulk electrons. (b) Population by excitation from Al III ground by the bulk and Auger electrons. (c) Population by radiative decay from the $2p^5 3s3p$ and $2p^6 3d$ levels. (d) Population by collisional deexcitation from the $2p^5 3s3p$ and $2p^6 3d$ levels. (e) Population by photon and electron (Auger and bulk) ionization from Al II $2p^6 3s3p$ levels. (f) Depletion by photon and electron (Auger and bulk) ionization.

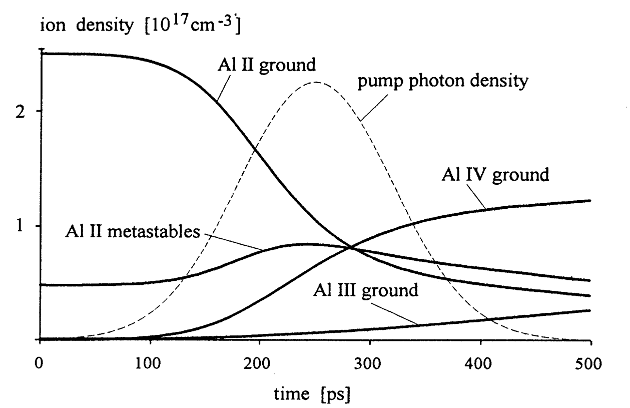

FIG. 5. Evolution of the ionic densities in the lasing medium. (The pump photon density is not shown to scale.)

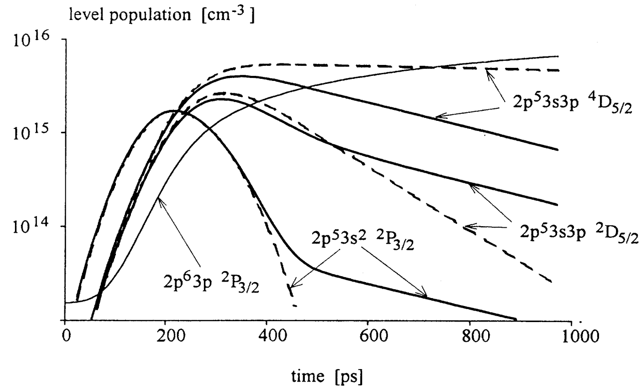

FIG. 6. Autoionizing level populations calculated with (full lines) and without (dotted lines) collisional mixing. Also shown is the population of the $2p^6\,3p\;^2P_{3/2}$ lower level.

V. CONCLUSIONS

We have modeled the population kinetics in a population inversion scheme in which the $2p^5(3s3p\;^3P)$ levels of Al III are populated by photoionization of Al II metastables using the N-shell quasicontinuum emitted by highly ionized Sb around 125 Å. Assuming that the quasicontinuum can be produced with a brightness of about 0.05 photons/mode, we estimate that a gain of a few cm^{-1} can be obtained for several $2p^6\,3p\;^2P$-$2p^5(3s3p\;^3P)\;\;^2P,\,^2D$ Al III transitions around 170 Å. The target is a cold and dense Al II plasma as that produced by high power stabilized arcs. The duration of the population inversion appears to be sufficient for the amplified light to travel a few cm along the lasing medium.

We could not assess the accuracy of the radiative and autoionization rates used in the model [4], and thus the gain we have computed for the proposed scheme is an approximate estimate only. However, the modeling demonstrated salient features of the inversion scheme based on $2p^5\,3s3p$ autoionizing levels.

(i) In a dense lasing medium, electron collisions help empty the lower laser levels and may prolong the inversion at low electron temperature.

(ii) The Auger electrons inherent in such a scheme rapidly heat the lasing medium and limit the duration of useful gain. It is thus useful to reduce to a minimum the production of energetic photoelectrons by near-threshold pumping.

We have also modeled in a preliminary manner an alternative version of the present scheme, in which the initial medium is a dense Al I vapor, photoionized by the Sb quasicontinuum. The results indicate that the early pulse of secondary electrons, resulting from inner-shell photoionization of Al I, may produce a very large population of Al II metastables approximately synchronous with the peak of the pump pulse. The Al III ions produced by autoionization from Al II $2p^5\,3s^2 3p$ levels [26] do not seem to constitute an obstacle for the population inversion, since, in the very cold and dense plasma which forms initially, these recombine very quickly to Al II levels. The gain achievable with such a dense Al I target is only slightly larger than for an Al II plasma due to the more severe Stark broadening of the lasing transitions. Also, the duration of inversion is shorter and the scheme probably requires traveling wave pumping for significant amplification [9]. However, the production of the target and the coupling of the pump photons may be much easier in this case.

In the light of the present results we believe that it might be promising to search for lasing ions of higher Z along the Na-like sequence. Besides the decrease in lasing wavelength, there may be the additional benefit of a reduction in the autoionization branching ratios of the $2p^5\,3s^2$ levels, the main culprits for the heating of the lasing medium. In addition, the N-shell quasicontinua proposed here for pumping will be that emitted by heavier elements in higher charge states, which are more compatible with the plasma conditions required for high brightness in the soft x-ray range [8]. In particular, a Si III–Si IV scheme for ASE at shorter wavelengths could be very attractive; the Si IV transitions of interest are around 125 Å [5]. In this scheme, the La quasicontinuum band centered at 93 Å and of about 4-Å width [8] may be used to photoionize the Si III metastables, and the target could be neutral Si in gaseous form (SiH_4).

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