Enhancement of x-ray gain in neon-like ions by direct collisional pumping with suprathermal electrons

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We propose and demonstrate quantitatively that a two-component electron distribution with the energy of the suprathermal tail approximately matched to the excitation energy of the upper lasing state results in greatly enhanced x-ray gain in neon-like ions. Such a configuration may be attainable in laser-driven plasmas.

In recent years considerable interest has centered on neon-like ions[1-3] in the search for plasma conditions which will promote population inversions conducive to lasing in the x-ray region of the spectrum. The attractiveness of the neon-like configuration stems from the fact that the proposed lower lasing level $1s^2 2s^2 2p^5 3s\ ^1P_1$ decays rapidly to the closed-shell ground state, whereas the upper lasing level $1s^2 2s^2 2p^5 3p\ ^1S_0$ is by comparison radiatively stable. It is the purpose of this Rapid Communication to present calculations which demonstrate that the gains to be expected from this naturally favorable system may be greatly enhanced by the use of a hot-electron component which enhances collisional pumping of the lasing states while the cold thermal electron component maintains the neon-like stage. Such a two-component distribution occurs in plasmas driven by high-power lasers of wavelength $\lambda \gtrsim 1\ \mu$m.

We have chosen neon-like iron (Fe XVII) for the calculation; the results are scalable to higher- or lower-atomic-number elements by appropriate adjustments in the parameters—in particular, temperatures and electron energies. All 27 ionization stages of iron are modeled mathematically; however, only Fe XVI, Fe XVII, and Fe XVIII contain excited-state manifolds. For Fe XVI we include the six excited states $2p^6 3p$, $2p^6 3d$, $2p^6 4s$, $2p^6 4p$, $2p^6 4d$, and $2p^6 4f$. For Fe XVII the $2p^5 3s\ (^3P, ^1P)$, $2p^5 3p\ (^3S, ^1P, ^3D, ^3P, ^1D, ^1S)$, $2p^5 3d$, $2s 2p^6 3p$, and $2p^5\ n = 4$, 5, and 6 levels are modeled. For Fe XVIII, the calculation includes the $2s 2p^6\ ^2S$, $2p^4 3s\ ^2P$, $2p^4 3s\ ^2D$, and $2p^4 3s\ ^2S$ states. Where only the principal or principal plus orbital quantum members are given above, the substates are combined according to the assumption of their statistical population. The above model is manageable and yet preserves a sufficient number of the important couplings to the lasing states with meaningful ionization dynamics.

The states are coupled via spontaneous decay, electron collisional excitation and deexcitation, collisional ionization, and radiative and dielectronic recombination. We employ the dielectronic recombination rates of Jacobs, Davis, Kepple, and Blaha[4] which have recently received substantial experimental corroboration.[5] Many of the important electron collision strengths are available in the literature[6] and have been employed. Additional electron collision strengths have been taken from Blaha and Davis[7] or calculated by Rogerson and Blaha.[8] Radiative recombination cross sections are taken from Barfield's[9] work or are calculated hydrogenically. Collisional ionization cross sections are from Refs. 10–14.

For comparison we have also employed the electron impact ionization cross sections for sodium-like Fe XVI of La Gattuta and Hahn.[15] These cross sections include inner-shell excitation-autoionization and are 3–5 times greater than those for direct ionization. Little effect on the gain results presented below for neon-like Fe XVII was noted.

Once rates coupling the states are obtained by integrating the cross sections across the electron distribution, the time-dependent rate equation for each level is advanced using the algorithm of Young and Boris,[16]

$$\frac{df_i}{dt} = \Sigma f_j W_{ji} - f_i \Sigma W_{ij} \ , \tag{1}$$

where f_i is the fraction of all ions in state i, and W_{ji} is the rate in $\sec^{-1}$ for the transformation of state j into state i. Two types of results are presented below: fully-time-dependent calculations, where a hot-electron component Gaussian in time disturbs a steady-state plasma, and steady-state results for the level populations, where $df_i/dt = 0$ for all states i. In all cases the plasma is assumed optically thin in all transitions. This is in a sense a conservative assumption, since the onset of opacity effects in the strongest neon-like transition, $2p^6\ ^1S_0$-$2p^5 3d\ ^1P_1$, has been shown[2] to enhance the gain by collisional coupling to $3p^1S_0$.

We have applied the model across a wide range of temperatures and densities with a single-electron temperature Maxwellian to predict the expected steady-state gain in the $2p^5 3s\ ^1P_1$-$2p^5 3p^1 S_0$ transition of Fe XVII at 255 Å. The gains found were at best 1–4 cm^{-1}. This low gain is principally due to the fact that the abundance of Fe XVII was found to peak below 200 eV at $\text{Ne} \approx 10^{19}$–$4 \times 10^{20}\ \text{cm}^{-3}$ and decline substantially at higher temperatures. This is expected since the coronal results of Jacobs *et al.*[4] show an abundance peak at 250 eV and, at present densities, collisions result in a substantially greater excitation state than expected in the low-density coronal limit. Since the ionization potential I_p of Fe XVII is 1266 eV, our results may be compared with those of Vinogradov, Sobel'man, and Yukov[2] which at $T = I_p/6$ for Ca XI show a gain of 1–10 cm^{-1}, depending on the density, for the optically thin case. The reason for the modest gains in both cases is that the upper lasing level is located at an energy above the ground state equal to ~ 4 times the electron temperature. Therefore less than 5% of the ambient electrons are capable of pumping the upper lasing level. It is for this reason that the addition of a hot-electron component is a promising technique for gain enhancement. However, the energy of the suprathermal component must approximate the excitation energy of the $3p$ state. We find that a suprathermal component of 100-keV electrons[17] provides additional ionization, not pumping of the upper lasing state leading to enhanced gain.

Our steady-state results for a monoenergetic hot-electron component at 800 eV (the $2p^5 3p\ ^1S_0$ level is 788 eV above the ground level) are presented in Fig. 1. The dramatic increase in gain with hot-electron fraction is due to direct collisional pumping of the $2p^5 3p\ ^1S_0$ level. Above 10% hots, the neon-like fraction is depleted by the increased ionization but the combination of a cold 70-eV thermal reservoir and a monoenergetic 800-eV electron component results in a substantial neon-like iron presence over a wide ratio of hots to colds. Note that the gain continues to rise even after the neon-like fraction has peaked; this is due to the increasing number of pump electrons. A peak gain of $\sim 40\ \text{cm}^{-1}$ is expected for a hot-electron density of $\sim 10^{20}\ \text{cm}^{-3}$ and a cold-electron density of $4\times 10^{20}\ \text{cm}^{-3}$. At higher ratios of hot electrons, ionization lowers the gain. Other steady-state calculations which have been performed for a fixed hot-to-cold electron-density ratio of 15% demonstrate that similar gains are achievable for cold-electron temperatures of 30–100 eV, and gains in excess of 15 cm^{-1} are predicted for cold-electron densities of 10^{20}–$3\times 10^{21}\ \text{cm}^{-3}$. Calculations employing a Maxwellian rather than a monoenergetic high-energy component show that little or no steady-state gain is achievable. This is due primarily to increased ionization of the neon-like stage to the fluorine-like stage by the high-energy tail of the Maxwellian. However, as seen below, a high-energy Maxwellian component may be effective in causing substantial transient gain enhancements.

Th results of our time-dependent-gain calculations are summarized in Figs. 2 and 3. In each case steady-state plasma of cold-electron density $4\times 10^{20}\ \text{cm}^{-3}$ is disturbed by the injection of a hot-electron pulse whose density is Gaussian in time, and peaks at $4\times 10^{20}\ \text{cm}^{-3}$, equal to the cold-electron density. Figure 2 displays the gain and neon-like fraction for a cold-electron temperature of 70 eV in a plasma disturbed by a 80-ps full-width-at-half-maximum (FWHM) pulse of 800-eV monoenergetic electrons. The corresponding steady-state case—as is evident from Fig. 1—results in an overionized plasma with a gain of $\sim 6\ \text{cm}^{-1}$ in the lasing transition. However, the injection of the 800-eV electrons in a pulse takes advantage of the

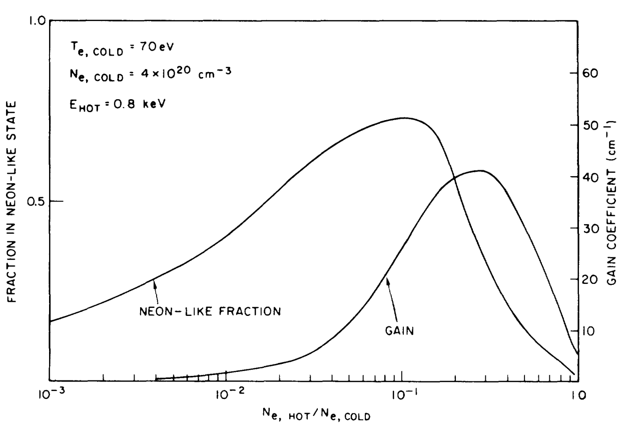

FIG. 1. Steady-state gain in the Fe XVII $2p^5 3s\ ^1P_1$-$2p^5 3p\ ^1S_0$ transition is plotted as a function of the ratio of 800-eV monoenergetic electrons to 70-eV thermal electrons, for the indicated plasma conditions. The fraction of all ions in the neon-like stage is also shown.

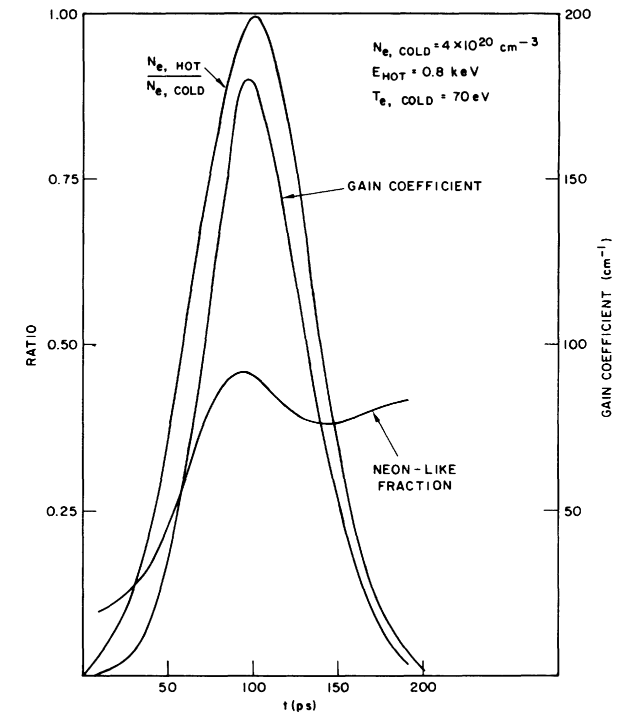

FIG. 2. Time-dependent gain coefficient for the lasing transition of Fig. 1 is displayed along with the neon-like ionic fraction and ratio of 800- to 70-eV thermal electrons. The plasma is assumed in a steady state at the hot-electron pulse onset, with a cold-electron density of $4\times 10^{20}\ \text{cm}^{-3}$ and temperature 70 eV.

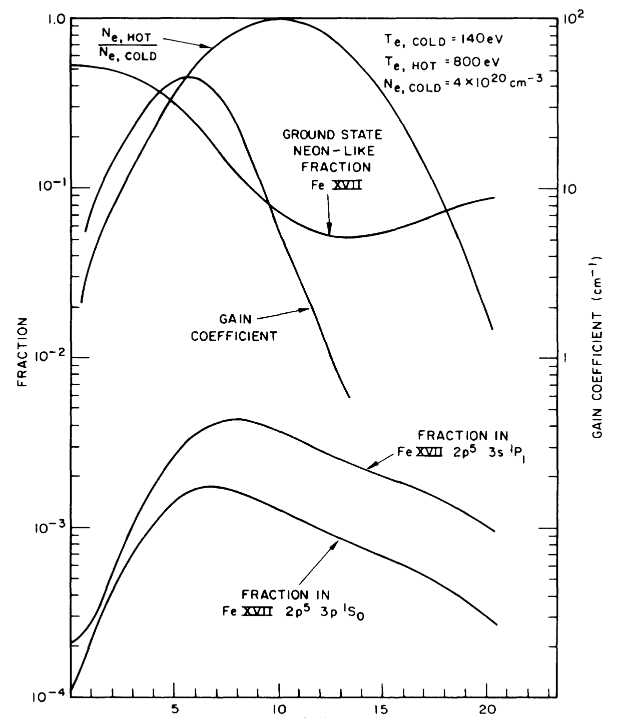

FIG. 3. Time-dependent hot-to-cold electron ratio, neon-like fraction, and gain coefficient are displayed. Also shown are the fractions of all ions in the upper and lower lasing levels. The plasma is assumed to be in a steady state at the hot-electron pulse onset, with a cold-electron density of $4\times 10^{20}\ \text{cm}^{-3}$ and temperature of 140 eV. The hot electrons are assumed Maxwellian with a temperature of 800 eV.

transient phase lasting ~ 50 ps, where about half the ions are in the neon-like stage. During those 50 ps the gain reaches $\sim 180\ \mathrm{cm}^{-1}$ because one has plenty of neon-like ions to pump combined with a large density of pumping electrons—which on a steady-state basis produces too much ionization.

In Fig. 3 a steady-state plasma of cold-electron temperature 140 eV is disturbed by an 8-ps FWHM pulse of hot electrons whose distribution is assumed Maxwellian at a temperature of 800 eV. The high-energy tail of the Maxwellian reduces the ionization time considerably—35% of an 800-eV Maxwellian distribution lies above the ground-state ionization energy of 1266 eV. Therefore, a shorter pulse is required. This also requires a hotter cold-electron temperature to insure that a large fraction of the ions are already in the neon-like stage when the pulse begins. Before ionization and collisional mixing reduce the gain, a rapid initial increase in the population of the upper lasing state pushes the gain to a peak of $\sim 45\ \mathrm{cm}^{-1}$. Following a period of high gain which lasts 5–10 ps, rapid ionization and collisional mixing, which increases the population of the lower level, sharply cut the gain. A monoenergetic pulse or any distribution which confines the pump electrons to energies ~ 800–1000 eV will result in a substantial gain over a wider range of conditions than a Maxwellian.

We now turn to considerations of experimental feasibility. The most promising approach would utilize the fact that hot electrons are continuously produced near the critical surface when plasma is irradiated at high intensity by lasers of wavelength $\lambda \gtrsim 1\ \mu\mathrm{m}$. For Nd-glass lasers at 1.06 μm the critical density is $N_e = 10^{21}\ \mathrm{cm}^3$, which is well within the electron-density range where enhanced gain is expected. The relationship between laser irradiance I ($10^{16}\ \mathrm{W\,cm}^{-2}$), cold-electron temperature T_c (keV), and characteristic hot-electron energy T_H (keV) is given by the quasiequilibrium theory of Forslund, Kindel, and Lee[18] (which is supported by experiments),

$$T_H \sim 14(I\lambda^2)^{1/3} T_c^{1/3} \quad . \tag{2}$$

Therefore, for $T_c \sim 70$ eV, $T_H \sim 800$ eV, and $\lambda = 1.06\ \mu\mathrm{m}$, nearly ideal gain conditions (Fig. 1) would be achieved at an irradiance of $\sim 2.5 \times 10^{13}\ \mathrm{W\,cm}^{-2}$. Moreover, Eq. (5) of Ref. 18 predicts a hot-electron fraction of ~ 0.12 under these conditions—also very close to ideal. Carman and Chapline[17] have designed a laser-irradiated target which would produce 0.8 cm of gain length. The above considerations obviously do not constitute proof that the proper conditions may be achieved, but clearly indicate considerable promise. Also, lasing at much shorter wavelengths may be obtainable by exciting the neon-like stages of higher-atomic-number elements. This would require both higher irradiances and higher suprathermal electron energies which can be specifically obtained for a given element from the results of Ref. 18.

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