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Non-Maxwellian Plasma Electrons in the Inversion Population of Ne-Like Ions

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Abstract: Level populations and line intensities are calculated for a pure Ne-like argon plasma showing their dependence on plasma parameters (electron temperature, density, plasma column diameter, electron energy distribution, etc.). It is shown that intensity ratios for 2-3 resonance transitions in the Ne-like ion can be used for plasma diagnostics. These intensity ratios are sensitive enough to detect the fraction of suprahot electrons in the plasma. Suprahot electrons cause a strong inversion effect for highly excited levels, e.g. 15:2p3p [J=0], 29:2s3s [J=0]. For these levels, collisional excitation strengths are large at almost any energy of impact electron above threshold. The inversion changes in time with a maximum at t ~ 80 psec at an electron density of $n_e \sim 8 \times 10^{18}$ cm^{-3}. The inversion increases with electron energy.

INTRODUCTION

Recent results indicate that plasma production based on a two-step process is effective in amplified stimulated emission (ASE) studies at short wavelengths. Such results have been reported for both capillary discharges plasmas and laser produced plasmas [1,2]. The time duration of the secondary discharge (laser pulse), and the time separation between the primary pulse and the secondary pulse are as important as the main discharge (laser pulse) parameters. Such experiments have been reported since 1991. However, there is no comprehensive explanation for experimental results. Typically the secondary discharge (laser pulse) is shorter than the primary discharge. The secondary impulse occurs when Ohmic (laser) heating dominates over electron collisional thermalization. Thus, the electron energy distribution is non-Maxwellian. In [3] the criteria are derived for the strengths of the current density (the laser intensity in a laser produced plasma) that are needed to drive the electrons into a non-Maxwellian state. Suprahot electrons has been studied for over a decade [4,5,6]. However, a description of the space and time evolution of the non-maxwellian electron distribution is an unsolved problem of physical kinetics. The lack of a realistic electron distribution function is one of the reasons that a magneto-hydrodynamic code has not been developed that predicts plasma parameters reliably.

Thus it might be useful to solve the reverse problem—to determine the electron non-Maxwellian distribution by spectroscopic means. The atomic kinetic code is needed to calculate the spectroscopic characteristics for plasma radiative emission. The code can also be used to search for the optimal plasma conditions for ASE. The atomic kinetic code should be based on the following criteria:

i)It must acccount for all important processes connecting the ions of adjacent multiplicity.

ii) The atomic constants for isolated ions and for elementary processes in the plasma should be calculated using the same self-consistent approach.

iii) It must be flexible and noncumbersome (with moderate computer requirements). Thus allowing generalization. Hence, a great deal of the calculation data can be drawn from principal conclusions and laws.

THEORETICAL MODEL DESCRIPTION

Our approach to the atomic kinetic problem is described in [7,8] where the spectra of Ne-like and Na-like ions are studied. Rydberg and autoionizing Rydberg states of Na-like ions were accounted for in [8]. 37 levels of Ne-like ions $2p^5$ 3l;$2s2p^5$ 3l are calculated precisely. The calculations account for all electron collisional and radiative transitions. Level populations for Na-like ions are calculated effectively. The F-like ions are not considered since low electron temperatures are assumed. Ne-like argon spectra at high electron energy are considered for a brief period in the system evolution ($t < 1.2$ nsec). Reabsorbtion is accounted for in the kinetic equations for all transitions. The key parameters of the model are electron temperature (T_e), density (n_e) and energy distribution. All of the results are for an argon plasma. However, general conclusions can be drawn for any Ne-like plasma. For brevity the key levels are given the following labels: #3—2p3/2 3s1/2 [J=1]; #5—2p1/2 3s1/2 [J=1]; #13—2p1/2 3p3/2 [J=2]; #15—2p3/2 3p3/2 [J=0]; #29—2s1/2 3s1/2 [J=0]; #17—2p3/2 3d3/2 [J=1];—#23 is 2p3/2 3d5/2 [J=1]; #27—2p1/2 3d3/2 [J=1].

RESULTS FOR A MAXWELLIAN ELECTRON DISTRIBUTION

The starting point for our calculations should be based on a well developed theory for plasma diagnostics for a Maxwellian electron energy distribution. We suggest that Ne-like plasma could be diagnosed by measuring the intensity ratios for 2-3 resonant transitions in Ne-like ions. Our model is used to calculate the time evolution of the level populations of Ne-like and Na-like ions. The time needed to reach steady-state conditions for level populations depends on the electron density. (See figure 1.)

Next we calculate the fraction of Ne-like argon as a function of electron temperature. We are looking for the lowest electron temperature at which Ne-like ions dominate the plasma. The results are given in Fig. 2. At $n_e < 10^{19}$ cm^{-3} a low electron temperature (about 20 eV) is enough to produce 80-90% of all ions in the ground Ne-like state. It can be seen by Fig.2. that a significant fraction of Na-like ions can exist at $n_e > 10^{20}$ cm^{-3}. At temperatures above $T_e > 45$ eV Fig. 2

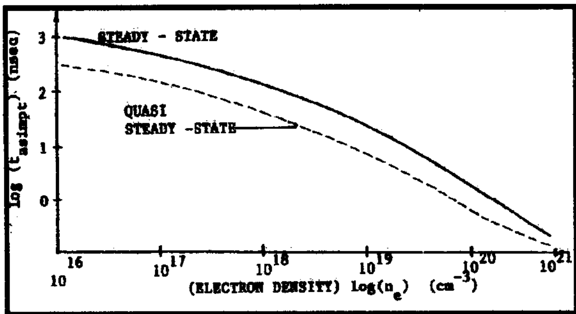

Fig.1. Time(t) to establsh steady state plasma conditions as a function of electron density (n_e). The time to steady state is almost independent of electron temperature and the plasma diameter.

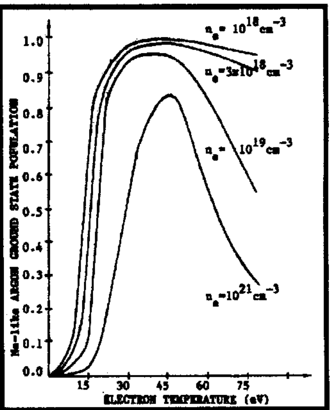

Fig. 2. Population of Ne-like argon ground state ions vs electron temperature.

is not correct because additional depletion occurs in the Ne-like ground state due to ionization. Fig. 3a shows the fraction of Ne-like argon ions as a function of electron density for a steady-state uniform plasma at T_e=75 eV. The pre-equilibrium electron density corresponds to the optimal plasma electron density for lasing. The pre-equilibrium electron density increases with the average electron energy in the plasma. The curves for the inversion population (Inv = P_u- g_u x P_l /g_l) as a function of electron density are illuminating. Curves for the inversion population relative to level #5 are shown in Fig. 3b, 4a and 4b for T_e= 75eV, 20eV and 150eV respectively. Note that under certain conditions inversion is possible relative to level #3.

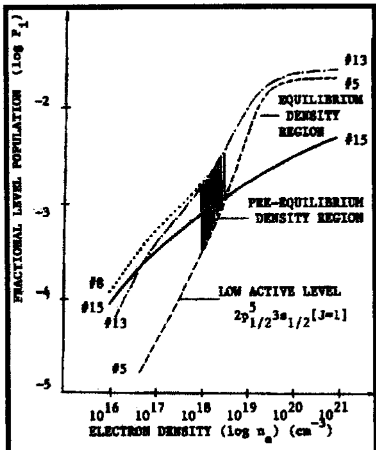

Fig. 3a Level population vs. electron density. T_e=75 eV, diameter, De=0.02 cm.

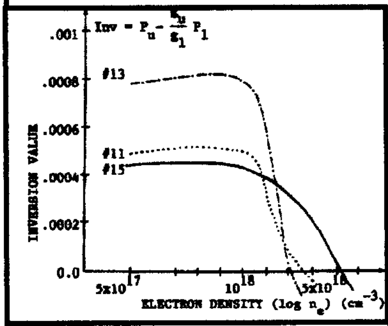

Fig.3b. Inversion population for levels #13,#15 vs. electron density at Te=75 eV, D_e=0.02 cm.

PLASMA DIAGNOSTICS BASED ON 2-3 RESONANCE TRANSITIONS

The seven brightest transitions to the ground state of Ne-like ions have

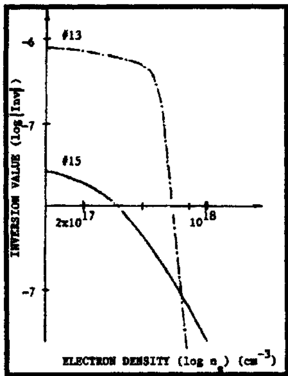

Fig.4a. Inversion population vs. electron density at Te=20 eV, De=0.02 cm.

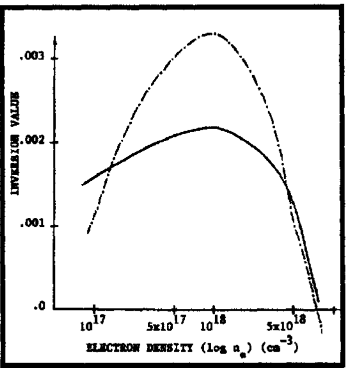

Fig.4b. Inversion population vs. electron density at T_e=150 eV, D_e=0.02 cm.

been studied both theoretically and experimentally. Line intensities of Ne-like ions are sensitive to the plasma parameters. Thus, the most prominent radiative transitions can be used as a tool for plasma diagnostics. However Ne-like ion line intensities are sensitive to the theoretical model used for their calculation. Hence a spectroscopic measurement of line intensities is also a way to test theory and bootstrap the diagnostic measurements. The first 5 resonance 3-2 [J=1 - J=0] electrical dipole transitions are in the wavelength region λ = 49.185 - 41.471Å for Ne-like argon. Their intensities can be measured simulteniously. Their intensity ratios contain information about electron density, temperature and the plasma diameter. Fig.5,6,7 show the rules for some line intensity ratios at steady-state, uniform conditions.

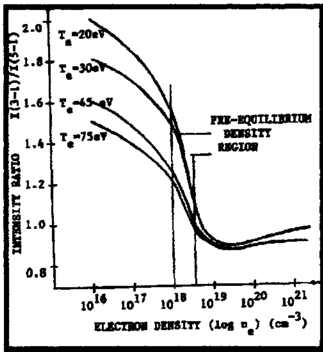

Fig.5. Ratio of intensities of two resonance transitions I(3-1)/I(5-1) vs.electron density. Data for D_e=0.1 cm and D_e=0.02 cm almost coincide.

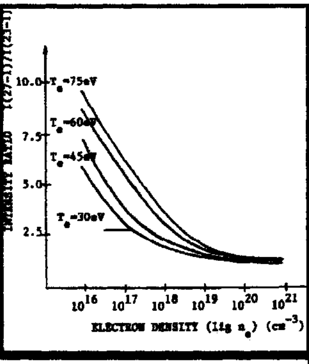

Fig.6. Ratio of intensities of resonance transitions I(27-1)/I(23-1) vs. electron density. Data for De=0.1 cm and De=0.02 cm practically coincide.

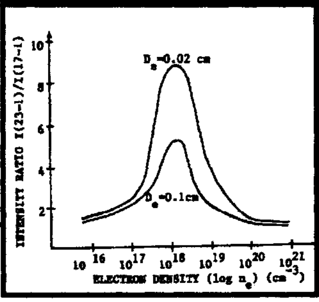

Fig.7. Ratio of intensities of resonance transitions I(23-1)/I(17-1) vs. electron density. Almost no dependence on electron temperature at 20<T_e<75 eV For these conditions the dependence on D_e is strong.

EFFECT OF SUPRAHOT ELECTRONS

Fig. 8 and 9 show the population inversion for levels #13 and #15. These figures plot the same parameters as Fig. 3b and 4a. However, the electron energy distribution in Fig. 8 and 9 each contain a hump due a distribution of suprahot electrons. The inversion population increases dramatically.

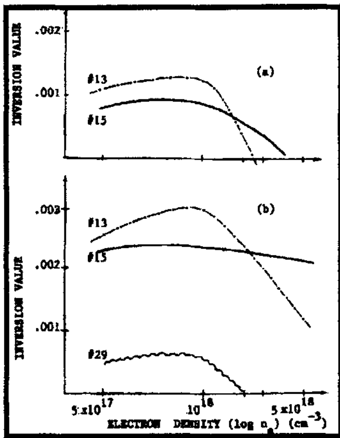

Fig. 8.The inversion population for levels #13 and #15 vs. electron density in the presence of suprahot electrons (a) 0.9 electrons at T_e=75 eV and 0.1 electrons at T_e=450 eV. (b) 0.5 electrons at T_e=75 eV and 0.5 electrons at T_e=450 eV.

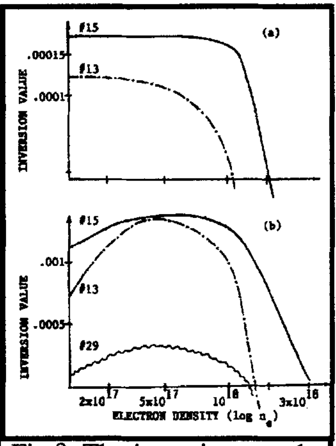

Fig.9. The inversion population for levels #13 and #15 vs. electron density in the presence of suprahot electrons (a) 0.9 electrons at T_e=20 eV and 0.1 electrons at T_e=450 eV. (b) 0.5 electrons at T_e=20 eV and 0.5 electrons at T_e=450 eV.

Note a high inversion population occurs for level #29 in Fig. 8b. The resonance line intensity ratios (Fig.5-7) also change. Thus, it might be possible to detect suprahot electrons with accurate spectral line intensity measurements. Our theory will be refined by accounting for the F-like ionization stage. However the model is well enough founded to indicate that non-maxwellian high energy electrons can create an inversion population for highly excited levels with J=0. Time for electron thermalization depends on discharge parameters and plasma conditions. However, one can state that at electron velocities of about 10^7 cm/sec and electron densities of 10^{18}-10^{19} cm^{-3} t_{therm} < 2 nsec (t_{therm} is the electron thermalization time.). Thus a short secondary discharge (t_{disch} < 1 nsec) will produce electrons that are high energy and quasimonoenergetic. Fig.10 (a-d) shows the time dependence of inversion population for levels #15 and #29 relative to both low active levels: #3 and #5 for a few values of electron densities.

Fig.10 shows that for higher electron density, the shorter time needed to reach maximum inversion.

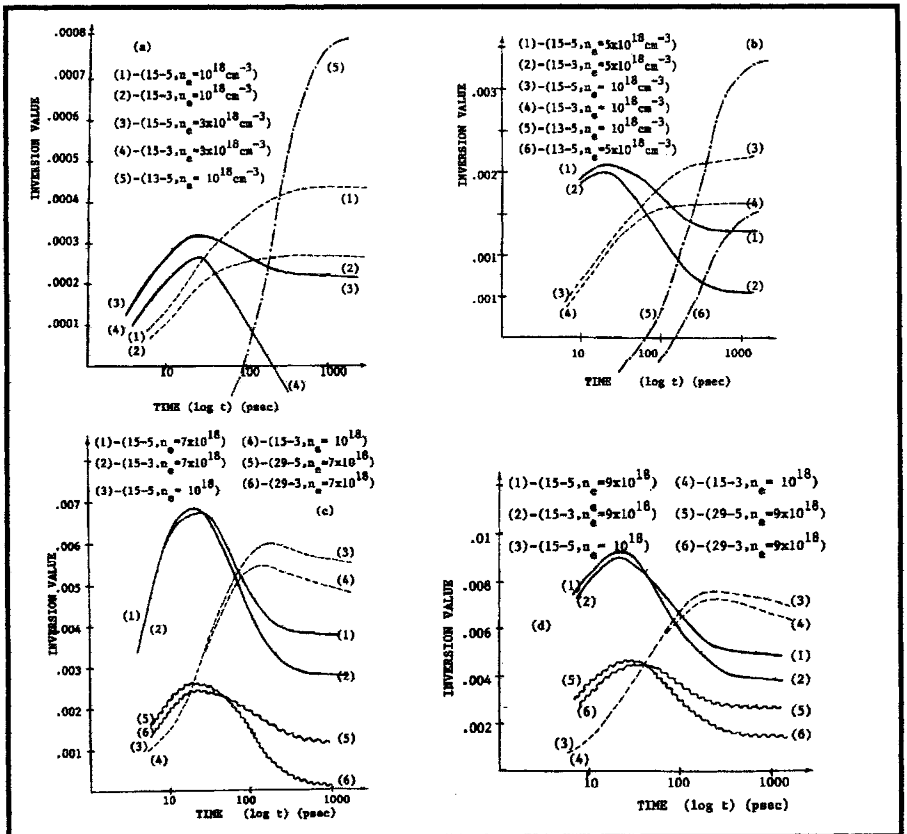

Fig. 10. Time dependence of inversion population relative to level #3, level #15 (λ = 430 Å) and level #29 (λ = 158Å) for several values of electron density. (a) T_e = 75 eV, (b) T_e=150 eV, (c) T_e = 450 eV, and (d) T_e = 1000 eV.

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