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NONSTATIONARY ARGON PLASMA, CONTAINING Ne-LIKE and Na-LIKE IONS. "FAST COMPRESSION" and POPULATION INVERSION.

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ABSTRACT. Evolution of levels populations in Ar plasma with varying parameters is under theoretical investigation. The model imitates fast compression and expansion of the capillary plasma column. The role of the HYDROGEN admixture is discussed.

INTRODUCTION and METHOD. We study the argon plasma under conditions where Ne- like and Na- like ions are the most abundant. This includes a sufficiently large region of plasma electron density N_{el} and plasma electron temperature T_{el} to be realized and investigated experimentally. Under these conditions in the steady state plasma with electron density $N_{el} > 10^{17}$, the population inversion for all pairs of lasing candidates is small, not more than 0.001 of the total number of argon atoms. Recently J.J.Rocca et.al. [1,2], in there experiments with capillary discharge showed, that the preionized plasma column with a diameter 0.2 cm can be rapidly heated by magnetic field arising during the fast increasing of the discharge voltage. The radiating region, under the influence of the compressing magnetic field, shrinks and its temperature increases. During the whole cycle of compression - expansion, the hot dense plasma never contacts with the capillary walls.

In [3] the idea of the simultaneous confinement and heating of the thermonuclear plasma inside tubelike powerful laser beam, has been suggested. We believe, that the same idea would be useful in the capillary discharge problem. The tubelike laser beam, enveloping capillary additionally compress its plasma due to ponderomotive forces and serves as an additional source of heating energy, that moderates the requirements to the characteristics of the discharge. As it is noticed in [3], such laser beam protects plasma against sausage- type instability.

The nonstationarity features in the compressing plasma, drastically influence the inversion of "lasing" levels population. The maximum of inversion does not obligatory coincides with the maximum of compression or temperature. Thus an appreciable inversion can appear at the decompression phase with moderate plasma temperature and relatively high electron density.

Here we investigate this question theoretically. A definite time dependence of the diameter D(t) of the compressing column, is accepted. The model of the Maxwellian homogeneous plasma, characterized by the correlated functions of electron temperature $T_{el}(t)$ and electron density $N_{el}(t)$ is considered. The $T_{el} \sim D^{-4/3}$ and $N_{el} \sim D^{-2}$ time dependencies follow from the simplest model of the homogeneous compression of the plasma obeying the local neutrality condition. Certainly it is a very simplified model of the process. Experiment shows that energy transfer between electro- magnetic field and plasma proceeds much faster than it follows from this model, possibly due to other physical processes in the plasma column. Nevertheless, we believe,that the accurate calculation of the evolution of the states populations in the plasma with the phenomenological time dependence of parameters of the active media, is a realistic way to evaluate perspectives of lasing, even if we do not specialize real physical processes that manifest itself in such a manner. Thus, we use here the terminus "compression" and "expansion", by convention, to designate some phenomenological model of the correlated variation of the plasma parameters.

In our calculations, we account for all the elementary atomic processes of the states population, in the framework of the collisional - radiational model. The rate coefficients of the processes changing the state of the Ne - like ion or Ne - like residue in the Na - like ion, are calculated due to the relativistic many - body perturbation theory with the model bare potential [4]. All the other rate coefficients are calculated in the semi - classical approximation. [5,6]. 37 basic states of the Ne - like ion and 37 multitudes of adjacent Rydberg states of the Na - like ion are accounted for. The infinite number of states of each Rydberg series is included. We investigated the role of the diffusion - like migration of the state of the system "Ne - like ion plus electron" over the overlapping Rydberg multitudes on the states population kinetics. It proved that the contribution of this migration into the relative populations of the states of the Ne - like ion is important, even in the case when Na - like ion states are poorly populated themselves. It is due to intensive population fluxes through these states and immensely large number of reaction channels. The summary effect of populating of Rydberg levels through dielectron recombination followed by different ionization processes, is very selective in relation to final state of system; it is important for creation of inversion.

Time dependent population calculations are based on our code [5], that solves the system of kinetic equations for populations of 37 lowest Ne- like levels and 37 population distribution functions for the multitudes of Rydberg states. Reabsorption of the spontaneous radiation for all transitions is accounted for due to the standard routine [7]. We considered the case of plasma cylinder with diameter 0.10 - 0.02 cm., the ion temperature is supposed to be equal to T_{el}. We experimented with the ion temperature function other than T_{el}: its reasonable variation did not change qualitatively the results presented below.

RESULTS. As usual, we numerate the states of the Ne - like ion in accordance with increasing energies. Special attention is paid to the states 3,5 and 6,8-15. The first two are assumed to be lower, the other nine - upper levels in the collisional - radiational lasing scheme. Transitions 15-5 (3p,J=0 - 3s,J=1) and 13-5 (3p,J=2 - 3s,J=1) are usually under especial attention in experimental and theoretical investigations. For the "compressed" column, with high temperature $T_{el} > 100\,eV$, three other transitions show high inversion. Those are: transition 37-33 ($\lambda = 520.5\,\mathring{A}$ and radiation transition probability $A = 3.2 + 09\,sec^{-1}$), 35-33 ($\lambda = 572.1\,\mathring{A}$, $A = 2.5 + 09\,sec^{-1}$), 34-33 ($\lambda = 572.4\,\mathring{A}\, A = 1.1 + 09\,sec^{-1}$). All wavelengths and transition probabilities are due to our calculations, see [5], and references therein.

Figure 1 shows evolution of the populations inversion for the transition 13-5 during the rather slow expansion starting from the steady state hot dense plasma. Two slightly different starting densities are considered. Line A: $N_{el} \rightarrow 35 + 16\,cm^{-3}$, while $t \rightarrow \infty$, $D \rightarrow 0,1$, cm.; line B: $N_{el} \rightarrow 30 + 16\,cm^{-3}$. The unambiguous transient effect manifests itself as increase of relative inversion

$$I(i-j) = \big(P(i)g(j) - P(j)g(i)\big)/P\,g(j),$$

where $P(i)$, $P(j)$ are levels populations, $g(i)$, $g(j)$ statistical weights, P- total number of Ne- like and Na- like ions that is close to the total number of Ar ions, for the processes here considered.

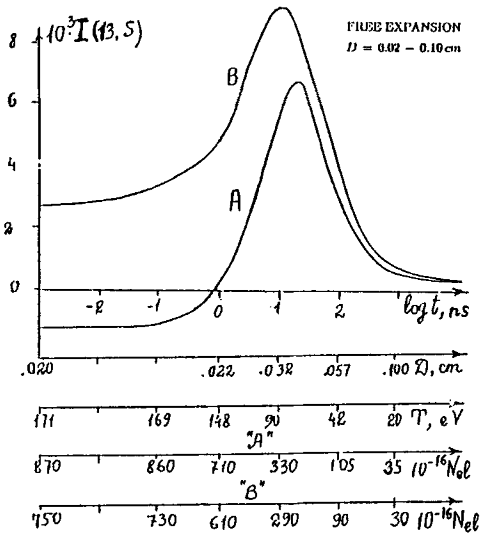
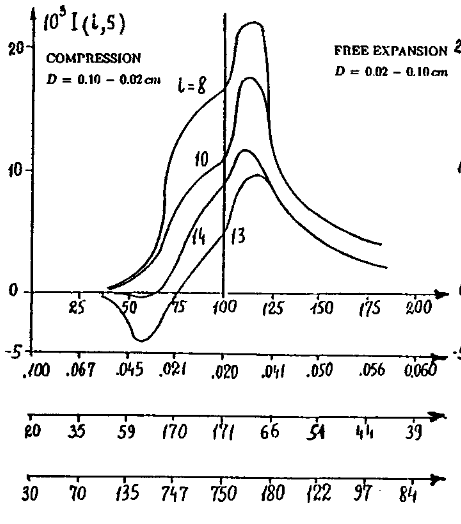


Figure 1

We see, that considerable inversion appears even if there is no asymptotical inversion for both steady states initial and final. This transient effect is due to thermodynamical relaxation of the ensemble of ions with overheated inner degrees of freedom. This effect is of the opposite sign, as compared with that predicted in [8] for "Ni - like Xe plasma". There, a short lasting (1 to 10 ps) increase of gain was predicted during the relaxation of the overcooled ions in the "strongly overheated plasma".

Figures 2 and 3 show evolution of the population inversion for some 3p-3s - transitions during the total cycle with moderate velocity compression and two different, moderate velocity, regimes of expansion: free expansion and delayed expansion, with $D(t)$ function symmetrical relatively to the point of the maximal compression.



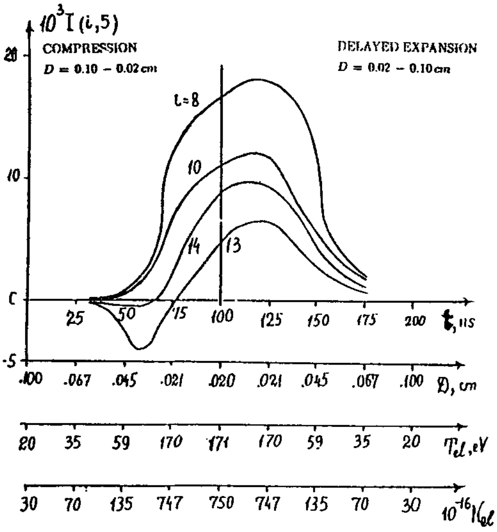
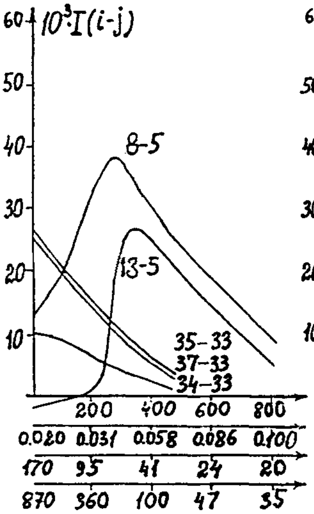
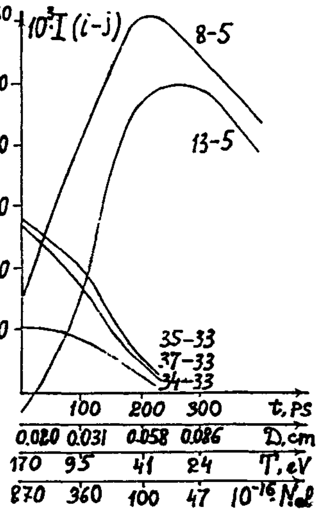


Figure 2...Figure 3.

In both cases, the inversion reaches its maximum during the expansion phase: the faster expansion the larger inversion. Figures 4 and 5 display the cases with the same as in figures 2 and 3, moderate velocity compression and fast (800 ps and 400 ps) expansion. Only decompression phase is presented. We do not discuss here how to realize such a fast changing of the parameters of the working media in the real device. The faster process seems to be impractical for the long (about 10 cm) capillary.

One can see a large transient inversion for two 3s-3p transitions, that remains sonsiderable even at the totally "decompressed" phase. Three transitions between the highest levels have large inversion at the "hot" phase, but expeience no transient phenomena. The same is for the 15-3 transition: no trannsient increasing of inversion for any regimes have been observed. It is due to the special mechanism of population of the level 15 as compared with other 3p - levels. It was discussed in [5].





.........Figure 4...................................Figure 5.

Hydrogen in Argon plasma. During the whole process, the average velocity of Ar ions never exceeds $2.0 + 06\,cm/sec$, electrons move 250-400 times faster. Because of the local neutrality condition, the rate of the matter compression or expansion is restricted by the low mobility of the heavy positively charged component. In our case this time is not less than 50 ns. Our calculations show that the transient effects are small in this case.

The rate of matter compression or expansion can be increased by introducing into the plasma the light positively charged component, with equivalent amount of electrons. This has been realized in [2] by adding a certain amount of H_2, that are totally ionized at $T_{el} > 20\,eV$. Now the transversal distribution of electron density can, in principle, change without changing of the density of heavy Ar ions. The relatively fast redistribution of protons maintain local neutrality of plasma. Thus, the presence of a light positively charged component opens a channel of the fast immediate exchange of energy between electro - magnetic field and the electron gas. Moreover, in the comprehensive MHD - model, this channel can play role of a trigger for the local fluctuations of plasma parameters and microturbulence phenomena. It is known, that plasma microturbulence, Lengmuir or ion- acoustic, present additional channels of energy transport [9].

The possibility to introduce an arbitrary amount of H_2 molecules gives us one new variable plasma parameter - the relation of electron density to Ar ions density. This can be used, in principle, as additional degree of freedom in searching for the optimal lasing conditions, even in a steady state plasma. We investigated this question using our kinetic code. The numerical experiments show, that the optimal relation is close to the value "8", inherent to the pure Ar - plasma with only Ne- like ions. The considerable amount of extra electrons will quench inversion, thus there must be an optimal amount of H_2, stimulating lasing effect. This was reported in [2] as experimental fact.

WORK in PROGRESS. Definite amount of the highly excited ($n > 3$) Ne- like ions and definite amount of the F- like ions appears when plasma is "hot",that reduces the population of the "working" levels. Our atomic code accounts for the $n > 3$ these states in a certain approximation, but they have been omitted in the kinetic equations. It can be justified to certain degree by the next arguments, that are especially reasonable in the case of low Z- ions.

Under plasma conditions, here treated, the region of phase space related to the states with $n > 3$ is essentially thermalized. We mean local thermadynamical equilibrium. Thus, the population fluxes therefrom are determined mostly by statistical weights of states and do not influence population inversion. The inversion arises due to selective redistribution of these fluxes in the beneath lying energy region.

The role of the highly excited Ne- like ion and of F- like ions is suppressed in the fast running processes because of their creation assumes a certain time - about or more than 10 ns for the cases here considered.

Nevertheless, we are working out now the code accounting for effectively the infinite number of the excited levels of the Ne- like ion and three lowest levels of the F- like ion. Code is based on the generalized Lotz formula [6].

Another direction of our work: evolution of the three component plasma in the magnetic field. Problem includes physical kinetics as well as quantum- mechanical aspects.

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