Complex computation of a high-brightness source in the soft X-ray spectral range based on He-like ions

M.Timshina[1,2], N.Kalinin[1], V. Burtsev[2], A. Samokhvalov[2,3]

[1] *Ioffe Physical Technical Institute, Russian Academy of Science, St.Petersburg, Russia*
[2] *«Burtsev laboratory» limited company, St.Petersburg, Russia*
[3] *ITMO University, St. Petersburg, Russia*

Abstract

Present work is dedicated to creation of high-brightness radiation sources in the range $\lambda<10$ nm using multiply charged ion plasma. In this paper, we numerically analyze the pumping of an active medium based on a plasma of He-like nitrogen ions.

Introduction

To date, work on creation of high-brightness radiation sources in the soft X-ray spectral range is currently undergoing. Interest to such sources is observed in biological and medical research, X-ray microscopy, plasma diagnostics, etc. One of the ways to create such sources is based on the use of multiply charged ion plasma. In this work, we compute pumping of an active medium based on a plasma of He-like ions.

Calculations for plasma of He-like ions were carried out earlier [1-4]. In this work, plasma of He-like nitrogen ions is used as an active medium since it is considered to be one of the most promising for obtaining amplification at a wavelength of $\lambda<10$ nm. In an experiment, the temperature and density of electrons are related by the dynamics of the plasma, i.e. their combinations are limited. That is why, we calculate gain coefficient for time-dependence of temperature and density obtained in advance in the hydrodynamic calculations.

Model description

The numerical study of active media of short-wavelength laser based on multi-charged ions plasma can be divided into several stages. The first stage involves calculations of plasma heating and dynamics. For this purpose, we used radiation magneto-hydrodynamic (RMHD) model in one-dimensional (1D) two-temperature (2T) axisymmetric approximation [5,6].

The calculations are carried out in following stages: at the first stage, the magneto-hydrodynamics, the non-equilibrium charge composition of the plasma and the supply circuit are calculated, and on the basis of these results, the level-by-level kinetics are calculated; then, for transitions with a clearly noticeable inverse population, the gain and the line intensity can be calculated.

The system of equations of radiative magnetic gas dynamics is written in Lagrangian coordinates. It takes into account plasma heating and the non-stationary ionization and recombination processes which are extremely important for the problem under consideration, as well as plasma cooling by its intrinsic radiation; the radiation of the continuous (bremsstrahlung, recombination) and linear spectra is taken into account. The magnetic field at the boundary of the plasma column is defined by the current flowing through it, which in turn is determined by the electrical circuit. The state of the plasma is described by generalized equations of state of the "middle ion" type. This system of equations takes into account the ionization by electron impact, photo- and triple recombination.

The population of excited levels of working ions is calculated in a quasi-stationary approximation, in which all coefficients are determined by local values of electron temperature, density and ion composition. The population inversion of operating levels and hence the gain factor are affected by the effect of resonance radiation capture that is taken into account using the Biberman – Holdstein method [7].

Results and discussion

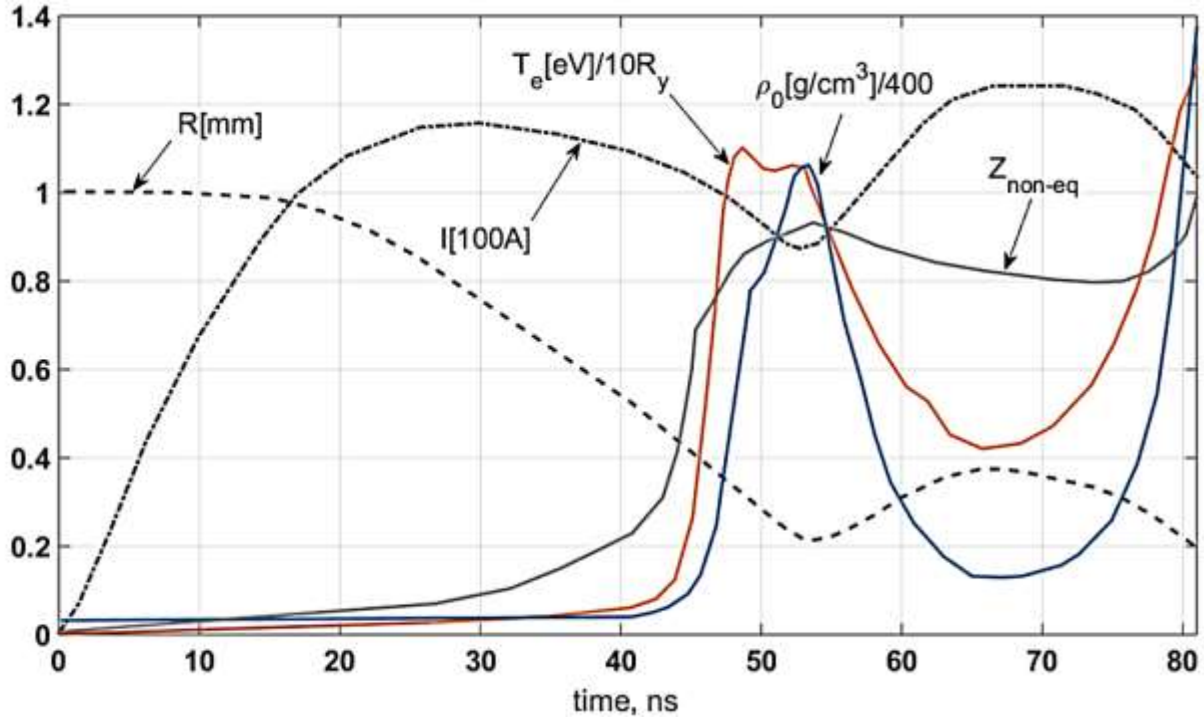

Fig.1. Characteristics of the plasma column on the axis up to 81ns. The dashed line shows the radius of plasma column, the dash-dotted line – current through the electric circuit, the orange line – electron temperature, the blue line – plasma density, the grey line – non-equilibrium average charge. The units are indicated in the figure.

This paper presents the results of the model described above for the following case: to the capillary voltage pulse with 100kV amplitude and 1-2ns front rise time is applied. The length of the capillary – 5cm, the interior radius – 1mm. The capillary is filled by nitrogen at 20Torr pressure. In our case plasma is created using discharge.

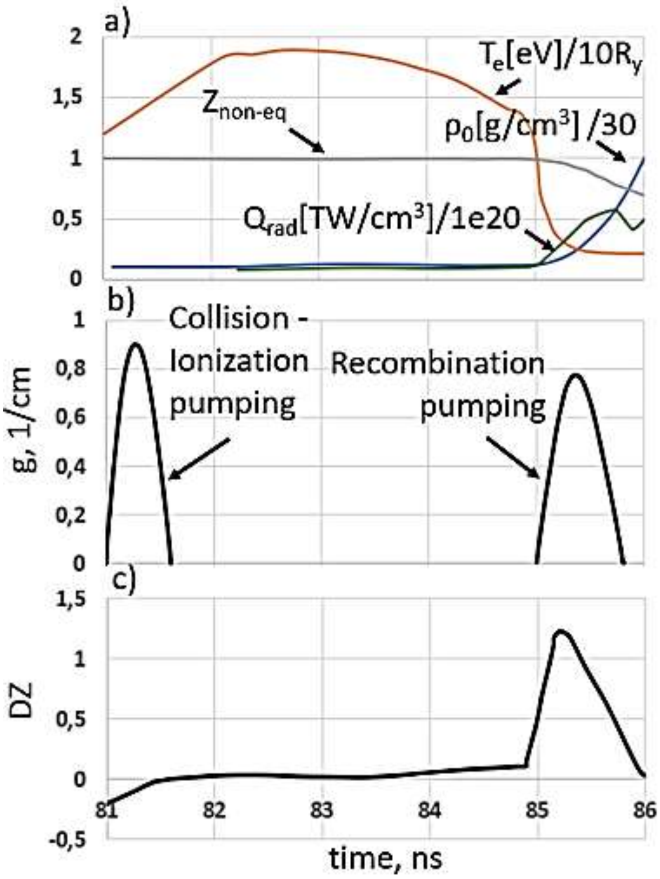

Fig.2. Characteristics of the plasma column in the axis after 81ns. a) The orange line shows electron temperature, the blue line – plasma density, the grey line – non-equilibrium average ion charge, the green line - plasma intrinsic radiation; b) gain coefficient for $3^1D - 2^1P$ transition (with wavelength 4.6nm); c) difference between non- equilibrium ion charge and equilibrium charge.

Figure 1 shows different plasma characterictics on the axis of the capillary. According to the line that illustrated radius of plasma column one can observe compressions, and the second one is due to the second rise in current. Thus there is two-step compression in this case. The reason for the appearance of the second increase in current in doubling in voltage due to the presence of a double forming line in the electrical circuit.

At the moments of the greatest compression, maximums of electron temperature and plasma density are observed. It should be noticed that ion temperature is not shown in the figures because (both figure 1,2) it is almost in line with electron temperature. The temperatures reach ~230eV at the maximum value, the initial temperatures are 10eV.

Figure 2 presents information about plasma evolution after 81ns in a more detailed time scale. Average charge reaches its maximum which corresponds to the case of a fully ionized plasma. In figure 2a one can see the phenomenon of «radiation collapse»: with the increase in temperature, the power of losses for its intrinsic radiation increases. If the power of radiation losses exceeds the power of the heating sources, the plasma is cooled. This way it became possible to obtain recombination pumping in pinching plasma. To determine where recombination or ionization-collisional pumping can be expected, one should analyze the difference between average non-equilibrium and equilibrium charges. If the difference is positive, recombination pumping can happen and vice versa. Figure 2c shows such difference DZ= Z_{non-eq}-Z_{eq}.

Figure 2b illustrates gain coefficient for line radiation with wavelength 4.6nm. It corresponds to the transition $3^1D - 2^1P$ in He-like ions. Firstly, the figure 2b matches the figure 2c well in the way described above. To calculate the gain coefficient, we use following formula for transition 3-2:

$$G_{23}[cm^{-1}] = \frac{A_{32}\,\lambda^3{}_{23}[cm](g_2 N_3[cm^{-3}] - g_3 N_2)}{8\,\pi\,\mathrm{c}\,\Delta\lambda_{23}/\lambda_{23}}$$

Where λ_{23} −wavelength of line radiation, $\Delta\lambda_{23}$ −line broadening, g_2, g_3- statistical weight of levels, N_2, N_3 −level population, A_{32} − spontaneous radiative transition rate. Gain coefficient for ionization-collisional case is a little bit higher than in recombination one. In both cases G_{23} is about $1cm^{-1}$ that is considered as perspective.

Conclusion

In present work the computation results for time-dependence of temperature and density obtained in the hydrodynamic calculations have been performed. Both recombination and ionization-collisional pumping of the active medium based on the plasma of He-like nitrogen ions have been obtained. The gain coefficients for the transition $3^1D - 2^1P$ in the both cases are close to 1 cm^{-1}.

Acknowledgments

The work was supported by Russian Science Foundation (Grant No. 20-38-90259).

References

[1] T. Ozaki and H. Kuroda, “Observation of gain on the 31D–21P soft-x-ray transition of helium-like nitrogen,” J. Opt. Soc. Am. B, vol. 12, no. 7, p. 1338, 1995.

[2] A.V. Borovskii, O.I. Zatsarinny, I.V. Kardash, and V.V. Korobkin, “Numerical calculations of the light amplification coefficients for short-wavelength transitions of helium-like ions in optically thin plasma,” Quantum Electronics, vol. 17, no. 8, 1990.

[3] Jancarek A., Pina L., Vrbova M., Tamas M., Havrikova R., Tomassetti G., Ritucci A., Vrba P. Nnitrogen capillary discharge emission in 1.9 – 2.5 nm wavelength range / Czechoslovak J. Phys. 2006. Vol. 56. Suppl. B. B250 – B25.

[4] Vrba P., Zakharov S.V., Jancarek A., Vrbova M., Nevrkla M., Kolar P. Pinching capillary discharge as a water window radiation source / J. Electron Spectroscopy and Related Phenomena. 184 (2011) 335 – 337.

[5] Derzhiev V., Zhidkov V., Yakovlenko S. Ion radiation in non-equilibrium dense plasma, Energoatomizdat, 1986. 160p.

[6] Borovsky A., Galkin A. Laser physics: x-ray lasers, ultrashort pulses, powerful laser systems. M: Izdat, 1996, 496 p.

[7] R. C. Elton, X-ray lasers // Academic Press, Inc. Harcourt Brace Jovanovich, Publishers. San Diego, 1990.