Two-stage compression of a plasma of multicharged ions created in a low-inductive high-current capillary Z-discharge as a method for pumping the active medium of short-wave lasers

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Abstract. The possibility of stepwise formation of the active laser medium on a plasma of multicharged ions is shown based on the numerical simulation results. Practically, such compression can be carried out with a high-voltage generator, storage and forming lines. It is presented that at conditions $I_m \geq 200 \text{kA}$ in stepwise pumping mode, it is possible to obtain Xe-plasma parameters with an electron temperature $T_e > 400 \text{ eV}$ and a concentration $N_e > 10^{20} \text{ cm}^{-3}$. Such plasma is a good medium for amplification of spontaneous radiation at several transitions in the spectral region $\lambda \approx 10 \text{ nm}$ in a Xe-plasma of Ni-like ions: it can provide a gain at the transitions $g+ \sim 1-2 \text{ cm}^{-1}$.

1. Introduction
Nowadays research aimed at creating efficient and compact lasers in the extreme ultraviolet (EUV) and soft x-ray (SXR) spectral range is considered promising for the tasks of x-ray microscopy, biotechnologies, etc. [1-9]. For such purposes, a high specific pumping power of the active medium is required [1-6]. For example, to obtain intense radiation with wavelengths $\lambda < 50 \text{ nm}$, it is estimated that the specific power of energy input into the plasma should be not less than 10 TW/cm$^3$. Active media based on Ni-like ions are considered to be the most promising for obtaining such radiation [10-18].

There are two common ways to create EUV-SXR laser medium on a plasma of multicharged ions: using high-power pulsed lasers with lower spectral frequencies and using high-current Z-discharges. The first approach has already allowed to achieve high pumping power density under laboratory conditions. Despite the fact that the second approach systems are inferior to laser-pumped ones in terms of specific power, they can successfully compete with them in terms of the received radiation energy in the pulse and the overall efficiency of the system. This advantage is due to the ability to create a longer active medium, which is usually about 10cm.

The result of the first experimental work with Ni-like ions was a significant advance in obtaining radiation in the SXR spectral region, including the "water window" region (2.3$<\lambda<4.4 \text{ nm}$). The shortest wavelength $\lambda=3.56 \text{ nm}$ was obtained in Au$^{51+}$ [10]. Experiments with Ni-like ions in laser-produced plasma showed a greater efficiency of Ni-like schemes compared to the Ne-like scheme, as the ration of lasing transition energy in Ni-like ion to the energy of its formation is much less than for Ne-like ion. However, the gain coefficients and brightness of the output laser radiation from the plasma of Ni-like ions were lower than from Ne-like ion plasma. In further research, two-and multi - stage laser plasma
pumping methods have been developed to improve the efficiency of Ni-like schemes [10], which are currently being successfully developed.

In order to obtain amplification of short-wavelength radiation in non-equilibrium Xe-plasma of Ni-like ions using capillary discharges, following conditions are needed [11]: a nanosecond growth front and amplitude of the order of 1 MA of current pulses. For practical implementation of the idea of creating an x-ray laser at Ni-like ion, it is necessary to find conditions for reducing these technically difficult requirements. This work is devoted to the looking for such conditions.

This paper presents the results of complex numerical study of the laser medium formation in the plasma of high-current capillary discharge for 4d – 4p, 0 – 1 transitions in Ni-like ions of Xe. The possibility of implementation a two-stage pumping of the active medium using supply systems described in [19] for obtaining of gain of the order of 1 cm⁻¹ or more, is analysed.

2. Model description
The modelling of active medium of lasers on a non-equilibrium plasma of multicharged ions includes several mutually related problems with different characteristic time scales: the ionization balance equations for determining different ion concentrations, the population balance equations of excited levels for determining the inverse population and amplification, plasma dynamic equations, which describe the space-time evolution of the density and electron and ion temperatures [1-4]. The characteristic times of ionization and hydrodynamic processes are of the same order, but the population balance of the levels is established to be much faster than the ionization balance. These circumstances make it possible to simulate the active medium in two stages: at the first stage, self-consistent calculations of the ion composition, heating, and dynamics of the plasma are performed, then, atomic-kinetic calculations of populations of considering levels, line intensities and gain coefficients are performed using the results of the previous stage. For such computations completely conservative implicit difference scheme is used.

![Figure 1. Scheme of discharge circuit consisting of a high-voltage pulse generator, a transport line and a capillary discharge load. Here the red cylinder depicts a reverse current line, the grey one - a capillary itself, and the yellow one - a plasma.](image)

The system of equations describing the ionic composition of plasma takes into account electron impact ionization, photo -, triple and dielectric recombination. The ionization and recombination coefficients were calculated using semi-empirical interpolation formulas from [2,3,20], plasma transport coefficients - from [21]. One – dimensional (1D) two-temperature (2T) radiation magnetohydrodynamic (RMHD) approximation [2,3,20] is used for numerical simulation of a high-current Z-discharge plasma.

The magnetic field at the boundary of the plasma column was determined by the current through electric circuit. The considered discharge power supply system (Figure 1) is based on a high-voltage pulse generator and a transport line with a given wave resistance.

Plasma radiation was calculated under the assumption that the plasma is transparent to its own radiation. The radiation of the continuous (bremsstrahlung, recombination) and linear spectra is taken into account [19]. 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 [1-3]. Considering transitions are illustrated in figure 2. The population inversion
of operating levels and the gain factor are affected by the effect of resonance radiation capture that is taken into account using the Biberman–Holdstein method [1-3].

Figure 2. The diagram of standard x-ray laser transitions.

3. Results

In our calculations we focused on the following parameter \( T_e \geq 400eV \ N_e \approx 5 \times 10^{20} cm^{-3} \), where according to [17] an effective amplification of spontaneous radiation in Xe-plasma is possible at several transitions: 4f-4d (2-1), 4d-4p (3-2), 4d-4p (0-1). Figure 2 presents the scheme for one of these transitions that we are considering in this work. The wave resistance of the transmission line is chosen \( R_p = 1 \) Ohm, the front of the voltage pulse is set to 1 – 2 ns with amplitude 200 kV, duration of the pulse -100 ns, the length of capillary is supposed to be 10cm, initial pressure - \( P_o = 4 \) Torr.

The calculation results are presented further. In figure 3 curves 1 and 2 respectively show time dependences of the discharge current and the radius of the external boundary of the xenon plasma. The time of the first current rise (~12 ns) is less than the time of the first plasma compression (~22 ns, where external plasma boundary reaches 0.22\( r_0 \)), which ensures a high efficiency of using the magnetic field to input energy into the plasma load. During the second compression stage, the current through the load reaches 220 kA. Such stepwise compression is not possible with the use of a capacitor bank discharge. By the time of the first compression, the electron temperature reaches the value of \( T_e = 690 \) eV, the plasma compression \( D = \rho / \rho_0 = 50 \), the average ion charge \( Z \approx 26 \), the electron concentration \( N_e \approx 6.5 \times 10^{18} cm^{-3} \). At the second compression the plasma compression becomes \( D = 62 \) (\( N_e \approx 8 \times 10^{18} cm^{-3} \)). At the considered pressure the temperatures of the ions and electrons almost match.

The average charge \( Z \) and charge of the most represented ion \( Y \) in the plasma are shown in figure 4. \( Y \) reaches the values of 26 after the first compression and remains constant until 35ns after that equal to \( Y = 27 \). The difference between \( Y \) and \( Z \) shows that the discharge is not equilibrium. Figure 5 presents in addition to figure 3 (where the characteristics on the capillary axis are indicated) spatio-temporal graphs of temperature \( T_e \) and ionization degree \( Z \).
Figure 3. Temporal dependence of 1 – current throw the circuit I/250kV, 2 - radius of the external plasma boundary r/r_0, 3 – plasma compression D/D_0/100 on the axis, 4 - temperature of electron T_e/690eV on the axis, 5 - average charge Z/54 on the axis.

Figure 4. The average charge Z and charge of the most represented ion Y on the axis.

Figure 5. Spatio-temporal graphs of temperature T_e (a) and ionization degree Z (b).

The results of calculating the gain for 4d – 4p, 0 – 1 transition are shown in figure 6. Note the qualitative agreement between the results $g^+(t)$ of our calculations and similar calculations performed for laser pumping [18]: for different temperatures, the dependence has a maximum, after reaching which it decreases sharply. The maximum gain values obtained in our calculations are less than the maximum gain values for the same transitions defined for laser pumping. The characteristic lifetime of a gain with $g^+(t) > 1 \text{ cm}^{-1}$ is on the order of several picoseconds.
**Figure 6.** Temporal dependences of gain $g^+$ for transitions 1 - 4f-4p ($\lambda = 13.2$ ns), 2 - 4d-4p ($\lambda = 9.9$ ns), 3 - 4p-4s ($\lambda = 17.3$ ns).

4. Conclusion

The possibility of stepwise formation of the active medium in high-current electric capillary discharge, is demonstrated that opens up prospects for creating compact and efficient sources of high brightness radiation on a plasma of multicharged ions in a wide spectral region, including the "carbon" and "water window" region. It is shown that at currents $I_m \geq 200$ kA in the step pumping mode, it is possible to obtain Xe-plasma with an electron temperature $T_e > 400$ eV and a concentration $N_e > 10^{20}$ cm$^{-3}$, that is enough to amplify spontaneous radiation with gain $g^+ \sim 1$ cm$^{-1}$ at several transitions with wavelength $\lambda \approx 10$ nm.

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