STUDY OF THE EMISSION FROM DIFFERENT-COMPOSITION PLASMAS INJECTED WITH A RELATIVISTIC E–BEAM ON A GOL–3 DEVICE

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*The first cycle of experiments on generation of high-power VUV radiation has been performed on a GOL–3 device. A preliminary theoretical analysis has shown that the energy of a relativistic e-beam (*100 kJ, 5 μs, 1 MeV*) can be effectively converted into the VUV radiation with the use of two-stage heating of a dense (*$n \sim 10^{16}$–10^{17} cm^{-3}*) plasma mixture. Such a plasma can be a working body for an ultraviolet laser. In experiments we have studied the parameters of dense plasma clouds with different mass balance of nitrogen, krypton, and hydrogen. It was shown possible to obtain a VUV radiation flash of* 5–50 MW *power and* 5 μs *duration in the scheme of two-stage heating of an active medium. The prospects for creation of a high-power ultraviolet laser based on the GOL–3 device are discussed in the paper.*

INTRODUCTION

High-power sources of radiation in the VUV and near X-ray ranges (hereinafter, VUV sources) are of great importance for a number of applications (see, e.g., Ref. 1).

At the same time, it is an independent physical problem to obtain sufficiently high-power radiation in this region. Up to date different sources of both coherent and incoherent radiation were studied many times. A review of these works can be found in Refs. 1–4. Usually to obtain an intense VUV radiation, two mechanisms are used for excitation of an active medium, namely, the excitation of atomic (ion) levels by the electron impact and the recombination excitation that appears at the stage of plasma decay. Other methods, such as photoexcitation or pumping of upper levels by atom or ion ionization, are less effective. Therefore, no consideration has been given to them in this paper. To obtain the emitting plasma, such ways as fast discharge near a surface in vacuum, explosion of thin wires, high-power laser pulse focused onto the surface of a target with a given composition are used most often.

In this paper we propose a new type of a source which differs from the above in both the way of formation of the emitting medium and characteristics of the latter. It is a hot plasma resulting from the collective interaction of a powerful microsecond relativistic e-beam with a gas or a precreated low-temperature plasma.

In the paper we first consider theoretically a possibility of obtaining a plasma with population inversion of levels emitting in the VUV on the GOL–3 device. Then we present a description of our experiments on creation of plasma with required parameters on the GOL–3 device and measurement of its emitting characteristics.

POSSIBLE SCHEMES OF PUMPING

Let us now assess the possibility of obtaining lasing in the VUV as far as concerned the GOL–3 device for some promising elements keeping in mind two ways of pumping: collisional and recombination ones.

A. Collisional pumping

This way of pumping is described by the equation: $X_o^{i+} + e \to X_u^{i+} + e$, where X^{i+} denotes an i times ionized atom, in which the pump occurs from the o level to the upper excited u level of one and the same ion. The rate of collisional pumping $P_{\rm col}$ (s^{-1}) of a bounded electron from the o level to the u level (energy difference $\Delta E_{\rm ou}$) is described by the expression[1]:

$$P_{\rm col} = N_{\rm e}\, C_{ou} = 1.6\cdot 10^{-5} \frac{N_{\rm e}\, f_{ou}\langle g_{ou}\rangle}{\Delta E_{ou}(kT_{\rm e})^{1/2}} \exp\left(-\frac{\Delta E_{ou}}{kT_{\rm e}}\right) {\rm s}^{-1},$$

where $N_{\rm e}$ is the electron number density; $C_{ou} = \langle\sigma_{ou} v\rangle$ is the coefficient of excitation rate averaged over the Maxwellian distribution function of electrons for the

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cross section σ_{ou} and the speed v; f_{ou} is the oscillator strength for the transition $o \to u$; g_{ou} is the effective Gaunt factor averaged over the Maxwellian distribution function. The dependence of the Gaunt factor on $\Delta E/kT$ is presented in Ref. 5.

In its simplest form, the laser with electron-collisional pumping includes $2P \to 3P$ excitation of a valent electron, where the $2P$ level is a ground state in the $1s^2 2s^2 2P^n$ configuration. The $3P$ level excites fast enough and it is metastable with respect to the direct radiative dipole transition into the ground state. Lasing appears at the transition $\Delta n = 0$ from $3P$ to $3s$ level. The neon-like isoelectronic sequence $2P^6$ shows the best characteristics in lasing. It is connected, in particular, with stability of neon-like ions in a nonstationary plasma.

Gain factor and line strength of the $3P \to 3s$ transitions were estimated for the plasma comprising ions of the following elements: aluminum, magnesium, and silicon; since just these elements at the expected plasma temperature (10–50 eV) are in the neon-like state. Our estimates are given in Table I.

TABLE I.

Ion	λ, Å	N_e, cm^{-3}	G, cm^{-1}	I_{ul}, W/cm^3
Mg III	1551	10^{16}	$3.5\cdot10^{-2}$	$8.4\cdot10^3$
		10^{17}	$4.9\cdot10^{-1}$	$1.2\cdot10^5$
Al IV	1481	10^{16}	$1.5\cdot10^{-2}$	$4.2\cdot10^3$
		10^{17}	$2.3\cdot10^{-1}$	$6.8\cdot10^4$
Si V	874	10^{16}	$2.4\cdot10^{-3}$	$5.7\cdot10^3$
		10^{17}	$9.4\cdot10^{-2}$	$2.2\cdot10^5$

It should be noted that these estimates have been done for the plasma consisting of ions of only this element. If the chosen element is considered as an admixture in a hydrogen plasma, the constant k can be introduced, which is the ratio of the admixture electron number density to the total electron number density. Then the population of the upper level N'_u, gain G', and line strength I'_{ul} are expressed through the presented parameters for a totally nonhydrogen plasma as follows:

$$N'_u = kN_u,\ G' = kG,\ I'_{ul} = kI_{ul}.$$

B. Recombination pumping

The process of recombination and subsequent cascading is described by the equation:

$$X_o^{(i+1)+} + 2E \to X_n^{i+} + E \to X_u^{i+} + E,$$

where subscripts o, n, and u are for the ground, intermediate, and upper lasing levels, respectively.

With plasma cooling down, as a result of recombination with electrons, ions are formed which have electrovalence less by one and are in the excited states. In this case the distribution over excited states differs from the Boltzmann equilibrium distribution, as a rule, because of higher population of the upper levels. To describe this process qualitatively, it is convenient to introduce the effective level n' such that for quantum levels lying above it the rate of collisional excitation exceeds the rate of de-excitation, whereas for levels lying below n' the radiative decay (de-excitation) prevails. In this case the population inversion can be achieved between the level u lying above n' and the level l lying below n'. The rate of three-particle recombination P_{rec}(s^{-1}) is described by the following expression[5,6]:

$$P_{rec} = 1.4\cdot10^{-31}\,\zeta^{-6}\,N_e^2\left(\frac{\chi}{kT_e}\right)^2 \exp\left[\frac{\chi}{(n'+1)^2 kT_e}\right]\ \text{s}^{-1},$$

where ζ is the ion effective charge from the "viewpoint" of the electron to recombine, χ is the ionization potential of the emitting ion; the effective level n' is described as[5,6]:

$$n' = 1.26\cdot10^2\left(\frac{N_e}{\zeta^7}\right)^{-2/17}\left(\frac{\chi}{kT_e}\right)^{-1/17}\exp\left[\frac{4\chi}{17(n')^3 kT_e}\right].$$

We have estimated gain and strength of spectral lines for C IV and N V ions. They are lithium-like ions which have transitions in the 1000–2000 Å range. The population inversion of the corresponding levels can be obtained with recombination of helium-like ions C V and N VI which dominate in plasma over ions with other electrovalence in the temperature range typical of the plasma in the GOL–3 device. The estimates obtained for $N_e = 10^{17}$ cm^{-3} are shown in Table II. We consider the transition between the levels neighbouring to n' (for N V $u = 5$ and $l = 4$). For helium-like ions it was taken that $\zeta \sim Z - 1$.

TABLE II.

Ion	n'	λ, Å	P_{rec}, s^{-1}	N_u, cm^{-3}	G, cm^{-1}	I_{ul}, W/cm^3
C IV	4.5	2530	$1\cdot10^5$	$2.9\cdot10^{11}k$	$5\cdot10^{-3}k$	$1.7\cdot10^2k$
N V	5	1620	$6.1\cdot10^4$	$5.7\cdot10^{10}k$	$6.3\cdot10^{-4}k$	$1.3\cdot10^2k$

EXPERIMENTAL SETUP AND METHODS FOR DIAGNOSTICS

Experiments have been carried out using the first sample of the GOL–3 device (see Fig. 1). The description of this device as well as its separate units and specifications can be found in Ref. 7. The GOL–3 device comprises an e-beam generator, a plasma chamber inside the solenoid with a uniform field up to 6 T at 7 m length and 12 T at isolated plugs at ends, a 10 MJ capacitor bank to supply the solenoid, the control and diagnostic units.

An electron beam with the energy of 0.8–0.9 MeV and duration of 3–5 μs is generated in a quasiplane diode with a graphite cathode 20 cm in diameter. The current density at the cathode reaches 200 A/cm^2. To increase the current density, the beam then is constricted in the magnetic field of a plug-type configuration and injected into the plasma chamber. In the experiments described, the e-beam current density in plasma was 1–2 kA/cm^2 at the beam diameter of 4 cm and its energy content of 40±5 kJ.

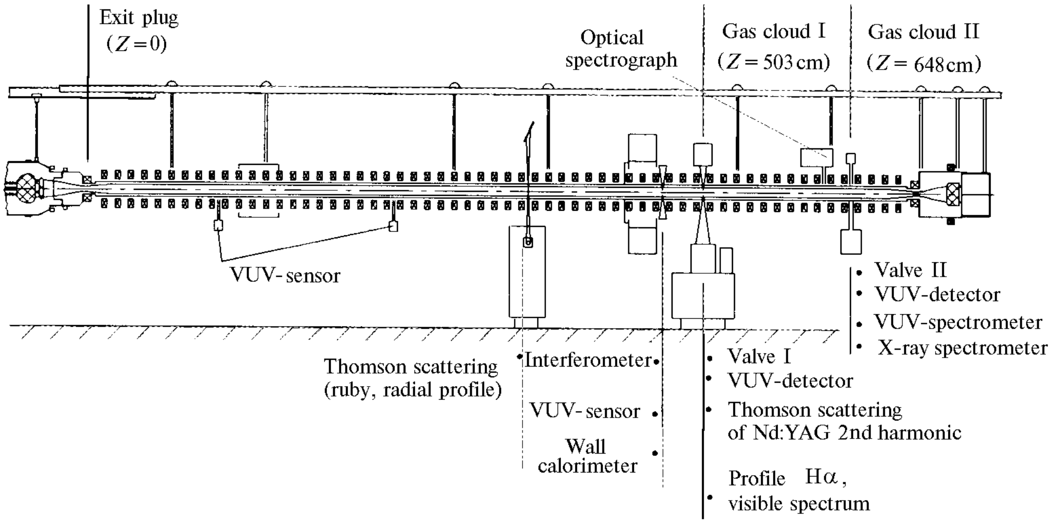

FIG. 1. The arrangement of the discharge chamber for generation of VUV radiation on the GOL–3 device. Special diagnostics are shown for determination of the parameters of active medium and radiation from plasma.

The diagnostic complex of the GOL–3 device allows one to measure the main parameters of beam, plasma, and beam-plasma interaction during a single shot. The initial energy of the beam electrons is determined from the voltage across the diode, beam currents in different parts of the device are measured by Rogovskii belts. In Figs. 2*a* and *b* you can see typical signals of the voltage across the diode of the accelerator and current of the beam generator.

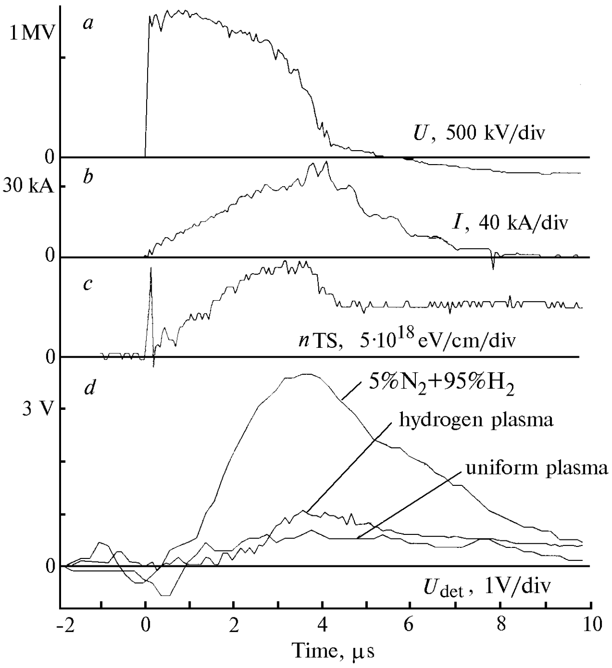

FIG. 2. Oscillograms of voltage across the diode of an e-beam generator (a), generator current (b), signal of the diamagnetic sonde placed at Z = 442 cm *(c) and oscillograms of signals of VUV detector (Z* = 503 cm*) for the cases of uniform hydrogen plasma, hydrogen cloud, and two-component cloud* N_2:H_2 = 0.05:0.95 *(d).*

Energy of the beam is determined with the help of a graphite calorimeter as well as by computing the integral $\int U_d I_b \mathrm{d}t$. From the difference between these two values the energy losses of the beam (~25%) are found. For measuring plasma parameters we used an optical interferometer with $\lambda = 3.39$ μm, diamagnetic transducers for measuring plasma pressure (signal of diamagnetic sonde placed at $Z = 442$ cm is shown in Fig. 2*c*), the multichannel detector of soft X-ray radiation, the system of Thomson scattering at the second harmonic of a neodymium laser. Energy spectrum of a beam at the output was recorded with the use of two analyzers different in the operation principle and a multilayer calorimeter. For detection of VUV radiation from plasma, vacuum photodiodes with aluminium photocathodes are used (see, for example, Ref. 8). They are used both with filters for the near VUV (LiF, MgF_2, CaF_2, quartz, aluminium) and without them.

Hot plasma trapped with a solenoidal magnetic field is itself the source of short-wave radiation. However, so-called two-stage scheme of plasma heating[9] seems to be more efficient for generation of VUV radiation on the GOL–3 device. In this case, in the solenoid with the help of direct discharge, a long column of hydrogen plasma (5 cm in diameter and 7 m in length) is formed which has relatively low density of the order of $3\cdot10^{14}$–$3\cdot10^{15}$ cm^{-3} (thin plasma) that provides efficient relaxation of an electron beam due to collective processes. At the same time, in the central part of the solenoid, at its short section the plasma of higher density (dense plasma) is formed with a composition optimal for obtaining a needed flash.

Beam energy emitted in the thin plasma is transferred to the dense plasma by ipithermal plasma electrons due to pair collisions, and then it goes into the emission with high efficiency in this small volume.

In such a way two aims are reached: high efficiency of the beam energy conversion into the energy of short-wave radiation (power of the order of 1 GW can be expected) and high brightness of the source.

As to the prospects on lasing, it is known that pump power per unit cross section of the plasma column, required to reach lasing threshold, must grow with the decreasing wavelength as λ^{-4}. Therefore, high power of medium excitation on the GOL–3 device is a very promising factor.

For generation of a powerful flash of VUV radiation we have equipped two specialized sections of the chamber. One of them (see Fig. 1) placed at Z = 503 cm (hereinafter Z denotes the distance from the input plug of the device) consists of a unit for pulsed gas leak-in integrated with the four-channel detector of VUV radiation, the system of Thomson scattering of the second harmonic of a Nd-laser and the detection unit (an objective and waveguides), as well as the instrumentation for spectrum recording in the visible. At 35 cm distance from the gas leak-in point toward the input of the device, the interferometer at 3.39 μm wavelength, the VUV radiation sensor, and the wall calorimeter are placed (in the same cross section of the vacuum chamber).

At Z = 648 cm the second pulsed valve for gas cloud leak-in is placed. The detectors of VUV radiation, the vacuum spectrometer of the VUV range, the spectrometers of UV and visible radiation, the X-ray spectograph with the X-ray electro-optical transducer (XEOT) are set in the same cross section.[10]

Main parameters of the dense plasma cloud at the point of pulsed gas leak-in amounted: number density $5\cdot10^{15}$ cm^{-3}, temperature 50 eV. Depending on the aim of an experiment the valve at either Z = 503 or 648 cm was turned on.

Different units of the GOL–3 device operate during the experiment in the following order. First pumped out discharge chamber is filled with hydrogen to the number density of 10^{14}–10^{15} cm^{-3}. The system for magnetic field supply is turned on. Before the magnetic field reaches its maximum, the pulsed valve actuates that leaks a local gas cloud with a preset composition into the discharge chamber. Then, after 500–1000 μs, the direct discharge is initiated that creates preionization. By changing pressure of the working medium and interval between the valve turning on and the start of the direct discharge, the required distribution of the gas cloud over the length of the device is selected. Within 15–30 μs after the discharge initiation, e-beam is injected into the plasma.

SPACE AND TIME EVOLUTION OF THE VUV EMISSION

Radiation from plasma was recorded with the four-channel VUV detectors placed at a distance Z = 503 cm in different modes of device operation: with a homogeneous plasma, with leak-in of the hydrogen cloud, with leak-in of 5%N_2 + 95%H_2 gas mixture.

Shown in Fig. 3 is the VUV detector signal amplitude vs. the beam energy in these two modes. It can be seen from the figure that the level of emission from uniform plasma is practically independent of the beam energy being constant almost everywhere (the signal amplitude of ~1 V). An increase in the signal amplitude with a leak-in of a hydrogen cloud is accounted for by the increase in the plasma density. At the same time, once the 5%N_2 + 95%H_2 mixture is leaked into the chamber, signals increase four to five times. Signals typical for these three modes of operation are shown in Fig. 2*d*. The zero point on the time axis corresponds to the onset of the beam, 5 μs later the beam terminates, and the signal drop is observed. It should be noted that in this place of the device the radiation was harder than 1050 Å since it did not pass through the filter made of LiF. It can be seen from the signal shapes that the plasma VUV radiation has maximum intensity during the beam injection. It is indicative of the following: excitation of atomic and ion levels by the electron impact occurs with their subsequent de-excitation.

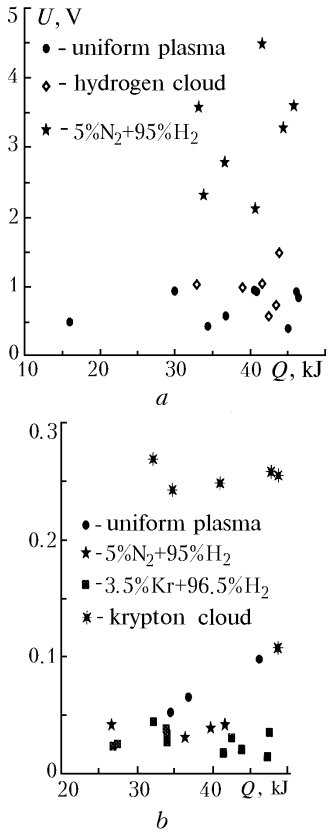

FIG. 3. Amplitude of a signal from the secondary-emission detector recorded from individual shots, Z = 503 *(a) and* 677 cm *(b).*

We have estimated the power of VUV radiation from plasma. With typical amplitude of a signal from VUV detectors equal to 4 V for the 5%N_2 + 95%H_2 mixture, the specific power of radiation was estimated to be no less than P_{min} ~ 9 kW/cm^3. With the characteristic length of the cloud $L = 1$ m and its cross section of 15 cm^2, the total power of radiation from the cloud should be no less than $P_{min} = 13$ MW, and the total energy per pulse should be no less than 65 J.

The energy coming to the chamber's wall was measured using a calorimeter. Based on these measurements, possible power of the VUV radiation from plasma can be estimated from the above (since the wall calorimeter detects the radiation energy transfer throughout the entire spectrum, from the visible to the X-ray radiation, as well as the energy transfer by neutral particles). The maximum measured heating of the receiving plate per pulse was 3.3 K, that gives us the estimate of the energy, falling on the wall, per unit length as 2.5 J/cm when we operate with the $5\%N_2 + 95\%H_2$ mixture. The total energy emitted over the entire length of cloud (~ 100 cm) is about 250 J.

We have also conducted the experiments with leak-in of pure nitrogen cloud. The profile of nitrogen concentration, optimal in the amplitude of VUV radiation, corresponds to the delay of e-beam injection with respect to the instant of the valve turn-on equal to 500 μs. Signals in this case were about two times greater than the level of the uniform plasma emission. When heating the pure nitrogen uniform plasma with an e-beam, the level of emission drops by about one order of magnitude as compared to the uniform hydrogen plasma. A characteristic signal is shown in Fig. 4.

In the experiments with separate leak-in of nitrogen and hydrogen with the use of assembly of two valves, amplitudes of signals of VUV detectors were very sensitive to the partial pressure of nitrogen and to the delay in the valve turn-on that also is connected with different content of nitrogen in the cloud. In this case, maximum signals did not exceed half of signals obtained from shots with leak-in of the prepared $5\%N_2 + 95\%H_2$ mixture.

The second cycle of experiments was conducted with leak-in of a cloud in the end of the device ($Z = 677$ cm), in the place where the vacuum monochromator and the XEOT are located. The radiation from plasma was detected in the same place with an analogous VUV detector. Shown in Fig. 3*b* is the signal amplitude as a function of the beam energy at the following modes of the device operation: with uniform plasma and with leak-in of clouds of $5\%N_2 + 95\%H_2$ mixture, $3.5\%Kr + H_2$ mixture, and pure krypton. Radiation in this place of the device is softer (more than a half of radiation from plasma passes through the filter of CaF_2 with the transmission threshold at 1200 Å). It can be explained by the fact that plasma is cooler here and cools down more fast due to closeness of the face of the device. As a consequence, the degree of ionization is lower and transitions are at longer wavelengths. Correspondingly, an addition of nitrogen has weaker effect on the power of plasma emission.

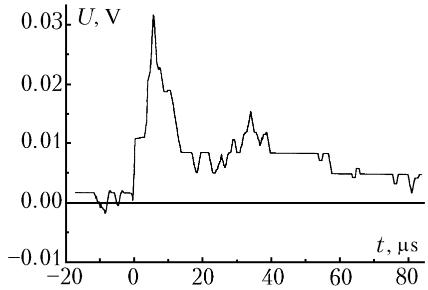

FIG. 4. Oscillogram of a signal from the detector of VUV radiation from nitrogen plasma (Z = 503 cm).

MEASUREMENTS OF X-RAY K-RADIATION YIELD FROM KRYPTON

In experiments we have also measured the strength of K_α ($\lambda = 0.98$ Å) and K_β ($\lambda = 0.88$ Å) spectral lines with leak-in of krypton cloud with the number density $n_0 \sim 10^{15}$ cm^{-3}. Emission at this lines was excited with an e-beam as well as with fast electrons resulting from the interaction of the beam with the basic hydrogen plasma with the density $\sim 10^{15}$ cm^{-3}. As a spectograph we used the plane graphite (002) crystal which reflects selectively X-rays in accordance with the Brady law. We have calculated the absolute value of the strength. To this end we used the results of Ref. 11, where the absolute calibration of XEOT was done in the corresponding region. Taking into account the coefficient of radiation reflection from the crystal and the film sensitivity, it was obtained that intensity of K-radiation determined mainly by the K_α line is about 1 kW/cm^3 (at the volume of the cloud of $2 \cdot 10^3$ cm^3 the total intensity of K-radiation is 2 MW that corresponds to 10 J energy emitted per pulse).

CONCLUSION

As a result of our experiments, the flash of UV radiation was obtained from plasma heated with an e-beam. Total energy of VUV radiation was estimated to be 50–250 J with the energy of the beam of 40 kJ. These results seem to be promising enough from the viewpoint of the following steps in the experiments, in particular, on optimization of the active medium parameters. It is also important to seek such conditions that would result in increase of the energy contribution into a dense plasmoid in order to increase the concentration of multicharged ions (with the same temperature) and to improve other parameters of the emitting plasmoid.

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