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Repetitively pulsed X-ray laser operating on the $3p-3s$ transition of the Ne-like argon in a capillary discharge

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Abstract. **The paper is devoted to a 469-Å X-ray laser excited by a fast capillary discharge in argon. The basic characteristics of the active medium and laser beam are presented. Applications of the laser in the studies of plasmas with densities of up to 10^{20} cm^{-3}, in interferometry, reflectometry, for analysis of materials, etc. are described. A brief historical review is presented and the current state of the art in the development of laboratory X-ray lasers is considered.**

Keywords: *X-ray lasers, capillary discharge laser.*

1. Introduction

X-ray lasers are now overcoming a border separating demonstration experiments from the development and starting up X-ray laser setups intended for applications. This is favoured by a number of factors: (i) the improvement of the methods for controlling the duration and temporal structure of laser pulses, which are used for creating the active medium of X-ray lasers; (ii) a great number of fundamental experimental and theoretical studies of gas-dynamic, kinetic, and atomic processes in a laser plasma; (iii) the development of the methods for diagnostics of a high-temperature plasma with a subnanosecond temporal resolution and a spatial resolution of 1–10 μm; (iv) the development of femtosecond lasers, etc. Large-scale X-ray laser facilities with a pulse energy of 0.1–1 kJ developed earlier are giving way to repetitively pulsed X-ray lasers, which can be sometimes mounted on a medium-size laboratory table. A significant amplification has been already demonstrated in the X-ray range for the pump laser pulse energy less than 1 J. A saturation has been achieved in a capillary discharge laser, and its average power in the repetitively pulsed regime exceeds 1 mW. A capillary discharge laser surpasses in its spectral range many third-generation synchrotron sources in both the average and peak power. Our review is devoted mainly to this laser.

The advancement to the short-wavelength range became one of the ambitious aims of quantum electronics from the outset. The first review devoted to X-ray lasers was published by A.G. Molchanov in 1972 and contained 44 references [1]. The author proposed, in particular, to seek an inverted medium by extrapolating the wavelengths of visible lasers along the isoelectronic sequences of ions. A hard X-ray region $\lambda < 2$ Å ($\hbar\omega > 6$ keV) attracted the greatest interest of researchers. In this region, unlike the VUV-soft X-ray region (1200 Å $> \lambda >$ 2 Å), radiation can again propagate in the air, as in the visible range. The mastering of this range is quite promising from the point of view of scientific and practical applications of X-rays. However, because of a number of fundamental problems, which become more complicated with decreasing the radiation wavelength, laser action has not been produced so far in the hard X-ray range.

At the same time, coherent radiation in the long-wavelength region (30 Å $< \lambda <$ 600 Å) is obtained by two methods: on the lines of multiply charged ions in a plasma (usually a laser plasma) and by generating high harmonics in visible lasers. Note that lasing was obtained in laboratory setups, and, as a rule, we are dealing not with devices but with experimental observations of lasing with pulse energies as low as ~ 1 μJ or even ~ 1 nJ. Output pulse energies up to a few millijoules were achieved in the 1990s on largest laser facilities. However, expensive experiments of this type are not performed at present. A review of the state of the art in the development of laboratory X-ray lasers is presented in [2] and the proceedings of the conference [3]. In addition, the large-scale projects on the development of free electron lasers are being financed at present. They are being performed at several international centres in different countries. The best results were obtained at the DESY synchrotron centre (Hamburg, Germany) where generation was produced in the range from 600 to 800 Å. The facilities for generating X-rays are based on electron accelerators with the beam path length of ~ 100 m.

A 469-Å capillary discharge laser considered in this review has been created at the Colorado State University (Fort Collins, USA). It is the only X-ray laser of the sort. Despite a large emission wavelength of the laser, we will use the term X-ray laser, as accepted by many authors. This laser operates in a repetitively pulsed mode and has an average output power of several milliwatts, which is quite sufficient for a variety of scientific applications.

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The review includes recent papers on the study of the active medium and the coherent properties of a capillary discharge laser beam, as well as papers on the laser applications in interferometry, analysis of materials, and some other fields.

It was a pleasure for us to prepare a review for this issue of Quantum Electronics devoted to the memory of N.G. Basov. Theoretical and then experimental papers on X-ray lasers were initiated and supervised at Basov's laboratory in 1972 by I.I. Sobelman, who considered from the outset a laser plasma as a potential active medium. Note that at the same time the studies on the creation of an inverted medium for the VUV spectral region by the photoionisation of atomic shells in gases were already performed by V.B. Rozanov [4, 5] at O.N. Krokhin's sector.

It became clear in 1976 that the highest inversion density can be provided in a high-temperature plasma containing the Ne-like ions [6]. In 1977, anomalies in the emission spectra of a laser plasma of calcium targets were observed, which suggested the laser action namely on the $3p - 3s$ transitions predicted earlier [7]. Later, experiments were terminated. However, theoretical studies of the active medium containing the Ne-like ions were continued to develop more realistic models taking into account the ionisation kinetics, gas-dynamic plasma expansion, and the nonstationary population of the excited states of ions [8–10]. A participant of these studies V.N. Shlyaptsev was invited to the Colorado State University, where investigation aimed at the creation of short-wavelength capillary discharge lasers had been performed under supervision of J. Rocca for several years. These investigations culminated in the obtaining of laser action in 1994–1998 and creation of a high-power repetitively pulsed 469-Å laser on the $3p - 3s$ transition of the Ne-like Ar. This laser, although being compact, has a time-averaged spectral power exceeding that of any modern synchrotron beamline in this wavelength range. This made it possible to perform a number of experiments (see section 6). Some of these experiments could be earlier performed only on synchrotrons, whereas for others (ablation) the instantaneous power of synchrotrons was not high enough. The main disadvantage of a capillary discharge X-ray laser is the absence of wavelength tuning. At present, studies are being performed by J. Rocca's group aimed at the creation of a capillary discharge laser emitting at a shorter wavelength of 132 Å (the $4d - 4p$ transition in the Ni-like cadmium) [11]. From the point of view of producing inversion, the Ni-like ions are similar to the Ne-like ions. However, they are more suitable for the advancement to the short-wavelength spectral region. As an active medium for X-ray lasers, the Ni-like ions were proposed by P. Hagelstein (see details in [12]).

The problem of laser resonators in the VUV and X-ray spectral regions was discussed already at the earlier stage of studies devoted to the active media of X-ray lasers. The analysis performed at N.G. Basov's laboratory in 1976–1977 suggested that it is possible to create multilayer X-ray optics [13]. E. Spiller (USA) came to this conclusion several years earlier as applied to astrophysical studies [14].

Multilayer X-ray optics is widely employed in studies on X-ray lasers first of all for controlling laser beams, radiation focusing, and imaging. At the same time, the scope of its applications is much broader, including space research, materials technology, microscopy, projection X-ray lithography, and synchrotron radiation. At present, investigations in these fields are being performed at several laboratories at the P.N. Lebedev Physics Institute (FIAN), as well as at some other institutes of the Russian Academy of Sciences (see [15]).

2. Active medium. The Ne-like ions

The active medium of X-ray lasers is a plasma containing multiply charged ions. This is related to an extremely high rate of the energy deposit to a substance, which is required to produce and maintain inversion at a level of practical interest. This can be illustrated as follows. For a constant density of the substance, the gain is proportional to λ^4, while the required rate q (erg cm^{-3} s^{-1}) of the energy deposit to the substance should increase proportionally to λ^{-5} [16]. For $\sim$ 100 Å, such high pump rates can be realised at laboratories only in plasmas produced upon irradiation of solid targets by focused laser beams (we do not consider here huge plasma facilities and nuclear explosions). The first experiment aimed at the creation of an X-ray laser in a laser plasma containing multiply charged ions was performed in France [17]. However, fundamental data on the properties of multiply charged ions (energy levels, probabilities of radiative and collision transitions, recombination cross sections, etc.) were scarce at that time. Also, no diagnostic methods were available for studying the plasma state with a temporal resolution of 1 ns and a spatial resolution of $\sim$ 100 – 10 μm.

In the following 15 years, along with the development of theoretical and experimental studies of multiply charged laser plasmas, different mechanisms for producing inversion between the energy levels of multiply charged ions were analysed: charge exchange, optical pumping, photorecombination, rapid plasma cooling or heating, collision excitation, etc. [12]. It is the latter mechanism with the use of the Ne-like ions (Fig. 1) that was chosen for the experimental realisation at N.G. Basov's laboratory. This was explained by two reasons [6]. First, because of a large difference between the ionisation potentials of the Na- and Ne-like ions, a greater fraction of the atoms of the target material represent the Ne-like ions in a broad temperature range.

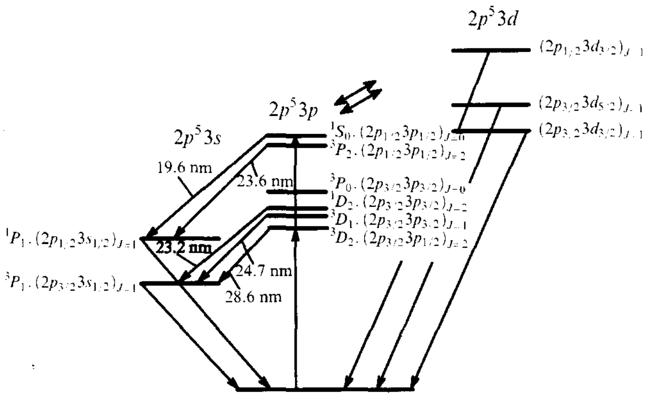

Figure 1. Energy level diagram of the Ne-like Ge XXII ion illustrating the main processes of excitation and radiative decay resulting in the inversion on the $3p - 3s$ transition. The wavelengths of laser transitions are indicated.

Second, the population inversion on the $3p - 3s$ transition in the Ne-like ions exists under stationary conditions. In other words, no rapid cooling or heating of the plasma is required to produce the population inversion. It is sufficient to maintain the plasma in a certain interval of densities and temperatures at which the thermodynamic nonequilibrium is produced due to line emission. The boundaries of these intervals and the gain were calculated in the region $\sim 50 - 500$ Å in papers [6, 18–20]. This spectral region corresponds to the $3p - 3s$ transitions in the Ne-like ions with the degree of ionisation from 10 to 25. However, because at that time the experimental data on the wavelengths were available only for ion charges $Z \leqslant 4$ (i.e., up to Al IV), the required wavelengths and transition probabilities were calculated [21].

The results of experiments on the observation of lasing in the Ne-like ions were reported in [7]. In these experiments, ~ 30-mJ, 2.5–5-ns pulses from a neodymium laser were focused on target (to a strip of width ~ 600 μm and length of a few millimetres). The resonator consisted of two mirrors between which a grazing diffraction grating was mounted. The feedback was carried out via the zero diffraction order, while radiation was outcoupled in the first diffraction order. An intense emission in the region ~ 600 Å corresponding to stimulated emission at the $3p - 3s$ transition of the Ne-like ion was detected on a photographic film. However, as mentioned above, these studies were not continued.

The efficiency of the Ne-like scheme was most conclusively proved later [22, 23] by directly measuring the gain rather than observing anomalies in the emission spectrum or estimating the value of the population inversion. In these papers, a unique laser setup was used producing 0.5-ns, several kJ pulses at the second harmonic of a neodymium laser. The radiation was focused into a line of length ~ 1 cm on a two-layer, thin freely suspended target of thickness less than 1 μm. Lasing was first observed in the Ne-like selenium ions at 209 and 206 Å. The laser pulse energy was ~ 1 μJ and the divergence of the laser beam was a few milliradians. Later, the energy of this X-ray laser was raised up to $\sim 1 - 10$ mJ, and it was used in diffraction experiments and for the imaging of biological objects with a spatial resolution of better than 0.1 μm [24, 25]. However, these works were not further developed. It became obvious that even for the study of applications of X-ray lasers, more compact setups are required, which would be accessible to many researchers or would be, at least, not so expensive.

During the following decade, investigations on X-ray lasers were mainly devoted to lowering the pump energy and the energy of laser drivers, as well as to the expanding of the spectral range of X-ray lasers.

A great success was achieved in studies [26, 27] where lasing in the Ne-like ions of copper, germanium, zinc, and gallium arsenide was obtained in the region $\sim 220 - 300$ Å; however, the laser parameters were substantially inferior than in [22, 23]: the pulse energy was 500 J for the fundamental (rather than second) harmonic of a Nd laser and the pulse duration was 2 ns. Massive solid targets were used instead of freely suspended thin films. Therefore, it has been shown experimentally that the requirements to the pump energy can be substantially alleviated, and studies with laboratory-scale setups are possible in the future. A list of groups involved in X-ray laser studies is presented in [28].

The most favourable conditions for producing lasing in a single-pass saturation mode ($gL \approx 15 - 20$, where g is the gain, L is the active-medium length) are achieved when a target is irradiated by two or three laser pulses. The first pulses prepare a homogeneous plasma column of length $\sim 1 - 2$ cm, while the last pulse produces inversion in the column. In [29], lasing in the Ne-like iron at 255 Å and $gL \approx 17$ was produced by this method. The total energy of a neodymium glass driver was ~ 30 J (cf. a few kilojoules in [22, 23]) and the pulse duration was 0.1 ns. In this case, one or two prepulses with the 2–5-ns delay were used, which contained $\sim 1\%$ of the energy.

The pump laser energy was further reduced by decreasing the pump pulse duration down to 1 ps. This idea was proposed by Y.V. Afanas'ev and V.N. Shlyaptsev at the department of FIAN headed by N.G. Basov [30]. The matter is that upon fast heating of electrons, the instantaneous values of the inversion can be one–two orders of magnitude greater than the stationary value (this question was discussed earlier in papers [31, 32]). Such a nonstationary scheme for producing inversion in the Ne- and Ni-like ions allowed the reduction of the pump laser energy down to 5–7 J (see review [2] and [33]). This scheme seems promising for the development of compact repetitively pulsed X-ray lasers pumped by laser pulses with energies up to 0.25–0.15 J [34, 35].

At present, only one repetitively pulsed X-ray laser is available whose average power allows its use for practical applications. The active medium of this laser is also Ne-like ions. However, the laser is pumped not by a visible laser but by a capillary discharge, which we will consider in the next section. (In sections 3–5, review [2] is used to a great extent).

3. Fast capillary discharge

Direct excitation of a plasma by an electric discharge has been always considered as a possible method for creating compact and efficient X-ray lasers. The main obstacle was the compression asymmetry and axial inhomogeneities of the plasma of high-power electric discharges, which appeared due to instabilities of different types. The situation has changed substantially after the achievement of saturation in a capillary discharge [36].

The use of a capillary discharge as an active medium for X-ray lasers was first proposed in 1988 [37]. Such discharges in evacuated capillaries made of organic materials were studied earlier from the point of view of their applications in spectroscopy, microscopy, and lithography [38–41]. However, except for one case (excitation of Teflon capillaries by a pulse with a rise time of 10 ns [41]), a capillary discharge plasma was produced by a rather broad current pulses with the rise time exceeding 50 ns. Under typical conditions, the plasma was generated by a discharge in a low-inductance capacitor (5–100 nF) through a circuit in which a capillary discharge plays simultaneously the role of a main discharge gap restricting the inductance. In this case, a large amount of the material detached from the walls restricted, as a rule, the electron temperature at a level of 60 eV.

In the X-ray laser, a capillary discharge with the current rise time of 10–40 ns is used. A short rise time restricts the amount of the wall material coming to the discharge before a magnetic field begins to compress the plasma by detaching from the walls [36, 42, 43]. In this way the problem of increasing (more exactly optimising) temperature and increasing the capillary plasma density was solved.

Another required parameter of the active medium containing the Ne-like ions is a high aspect ratio. The active region should be sufficiently long. In the case of cavityless lasing, the condition $gL > 25$ should be fulfilled. At the same time, the population inversion is produced, as mentioned above, due to the escape of resonance radiation. Therefore, the probability of absorption in the active medium should be small: $kd < 1$, where k is the absorption coefficient at the $3s - 2p$ transition depleting the lower laser level, d is the diameter or characteristic width of the active region. By combining these inequalities, we obtain

$$\frac{L}{d} > \frac{25k}{g}.$$

The quantities in the right-hand side of the inequality depend mainly on the properties of the ion and, to a lesser degree, on the electron temperature and density of the active medium. In particular, the estimate for the Ne-like ions is

$$\frac{L}{d} > 1000.$$

In addition, certain requirements are also imposed on the homogeneity of the active medium. Both the axial and transverse inhomogeneity of the electron density is extremely undesirable. The latter results in refraction, which limits the mean free path of photons, thereby restricting in fact the active-region length L. For the laser plasma, which is a strongly nonstationary and inhomogeneous object at the subnanosecond time scale and lengths 10 μm, refraction is a serious technical problem. This question was analysed in detail by V.A. Chirkov [44]. Note that in [37] and the subsequent studies of capillary discharge X-ray lasers performed at the Colorado State University, the problem of producing long, thin, and homogeneous plasma filaments was posed from the very beginning.

Diagnostics [42, 43, 45, 46] and simulations [36, 43, 47–49] confirmed that the fast capillary discharge plasma is an essentially nonstationary object. It rapidly contracts, is heated, and expands, representing a variety of the Z-pinch, whose properties depend substantially on the capillary walls. Such contracting capillary discharges have a number of qualities that are required for creating compact and efficient X-ray lasers. First, this is a high efficiency of formation of a high-density plasma containing multiply ionised atoms [42, 50, 51]. Second, this is the possibility of producing plasma filaments with a very high aspect ratio (up to 1000 : 1) [36, 52]. Third, this is a high axial homogeneity of the plasma being produced, which is provided by the homogeneity of the initial state, as well as by rapid compression and possibly by a stabilising role of the walls [47]. And fourth, this is a rapid motion of the plasma during laser irradiation, resulting in the dynamic Doppler shift, which facilitates the radiative depletion of the lower laser level [47].

Fig. 2 shows the scheme of a capillary discharge, which was successfully used to obtain saturation in the 469-Å line of the Ne-like argon [36, 42, 43]. The capillary was placed on the axis of a 3-nF capacitor filled with a liquid dielectric. The capacitor was charged through a Marx generator and then was discharged through a circuit containing a capillary and a discharge gap filled with SF_6. When 39-kA current pulses with a rise time of 75 ns were used, an argon plasma of length up to 20 cm was produced [52]. A more compact discharge device based on the Blumlein line was used to obtain coherent emission pulses with energies up to 25 μJ at 469 Å [53]. Later, an average output pulse energy of 0.88 mJ at a pulse repetition rate of 4 Hz was achieved at the same wavelength of 469 Å in a capillary discharge laser of nearly the same size [54]. The photograph of this laser is shown in Fig. 3.

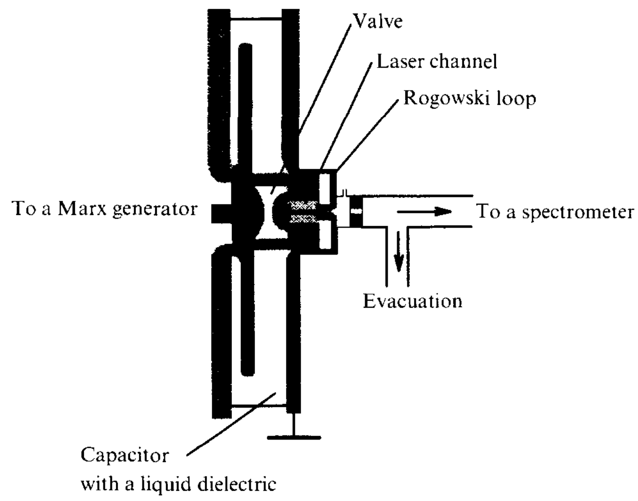

Figure 2. Scheme of a capillary discharge for producing lasing at 469 Å in the Ne-like Ar in the saturation regime [42, 43].

A more powerful capillary discharge with 200-kA current pulses with the rise time down to 10 ns was used to produce plasmas required for generation in a shorter-wavelength range [55]. A high efficiency of the generation of the multiply charged plasma by fast capillary discharges is illustrated by a remarkable similarity of two spectra of argon presented in Fig. 4 [51]. The first spectrum (Fig. 4a) was obtained in a capillary discharge with the 43-kA, 28-ns (full-width at half maximum) current pulse with the 13-ns rise time. The length of the capillary filled with argon was 2.5 mm [51]. The second spectrum (Fig. 4b) was obtained on the multiterawatt pulsed Gamble-II facility [56] at currents of the order of 1 MA. The similarity of these spectra suggests the similarity of the physical conditions in the discharges, despite a huge difference between the dimensions

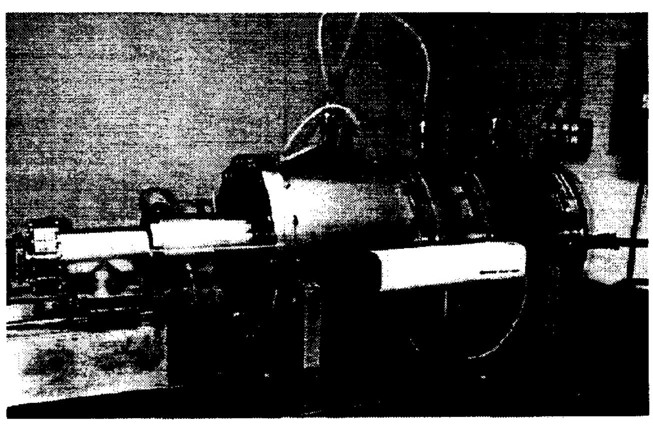

Figure 3. Capillary discharge X-ray laser with an average output power of ~ 1 mW. For comparison, a 5-mW helium-neon laser is shown in front of the X-ray laser (photo courtesy of the Colorado State University).

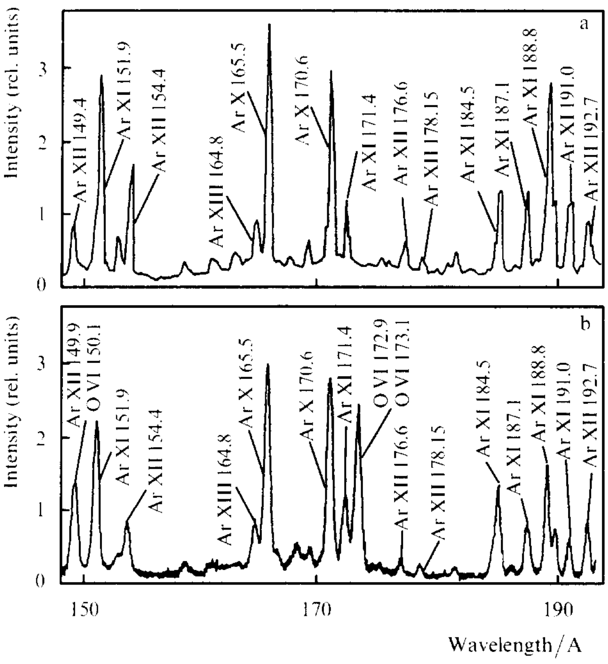

Figure 4. X-ray spectra of Ar obtained on the high-power Gamble II facility at a current of 1 MA and a few terawatt power (a) and in a capillary discharge of diameter 2.5 mm at a current of 43 kA and a current pulse duration (FWHM) of 30 ns (b).

of these facilities. For 51-kA current pulses in the capillary discharge, the electron temperature of the argon plasma of length 1.5 mm exceeded 150 eV [42]. The spectra of similar discharges in CaH_2 and TiH_2 showed that the electron temperature is sufficient for excitation of the upper laser levels in the Ne-like calcium and titanium [57].

The dynamics of the plasma of a fast capillary discharge is illustrated in Fig. 5. The figure shows the sequence of images obtained with the help of an X-ray pinhole camera placed at the end of a plasma column [45]. The plasma was generated in polyacetate capillaries of diameter 4 mm, which were filled with argon at as pressure of 700 mTorr. For the duration of the first half-period equal to 62 ns, the current was 39 kA. First the main part of the plasma and incoherent X-rays are localised neat the capillary walls (Fig. 5a). Then the electromagnetic force of the increasing current pulse generates a shock wave and rapidly compress the plasma down to 300 μm in diameter (Figs 5a–d). As follows from calculations, a substantial fraction of current (20 % – 50 %) flows through a substance detached from the capillary walls by the plasma emission or a thermal wave [36]. The optimal conditions for lasing upon collision excitation are produced a few nanoseconds before a maximum compression, when the first shock wave reaches the capillary axis. Then a plasma filament expands and is cooled (Figs 5e–g). The second, less significant compression, which is of no interest for the generation of X-rays, occurs later (Fig. 5h). Fig. 6

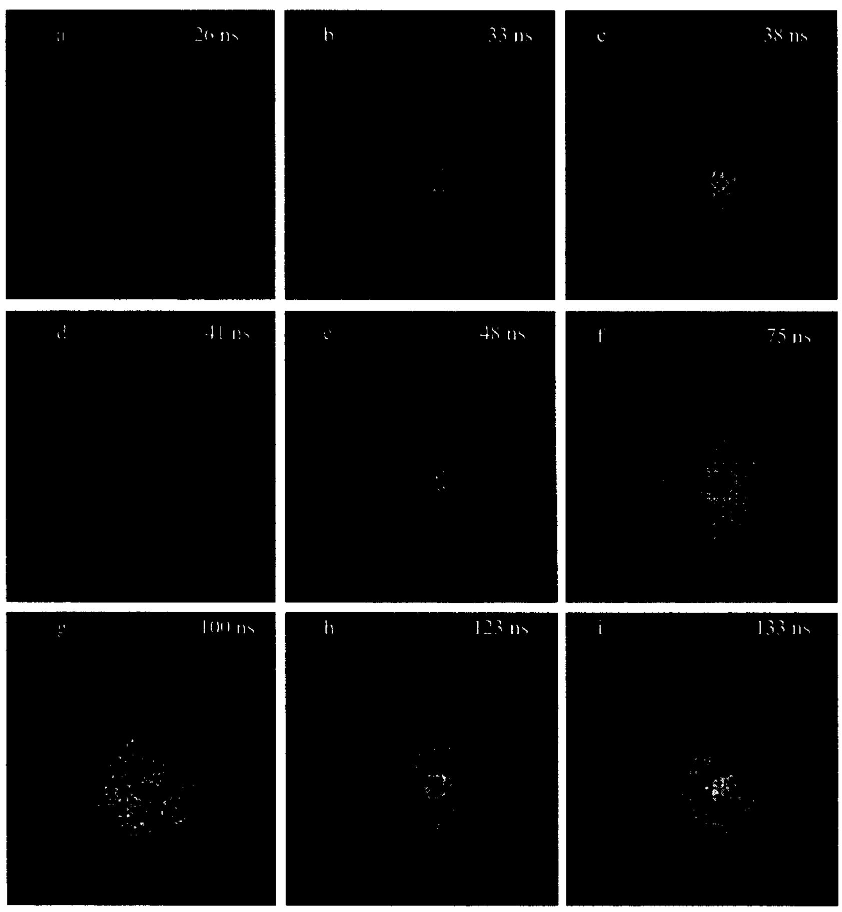

Figure 5. Sequence of images of a capillary plasma (view from the end): a capillary of diameter 4 mm and length 12 cm is filled with Ar at a pressure of 700 mTorr, the discharge current is 39 kA, the half-period duration is 62 ns. The images corresponding to a maximum compression (d, e) were obtained at a reduced sensitivity of a detector.

shows the calculated time dependences of the electron temperature and density near the axis of a capillary filled with argon and excited by current pulses with a first half-period of 70 ns. Laser action in the Ne-like argon ions occurs due to collision excitation at the instant when the electron density rapidly increases and achieves $(0.3 - 1) \times 10^{19}$ cm^{-3} and the electron temperature achieves 60–80 eV [36, 49]. Then, at the instant of the plasma stagnation, the electron density continues to increase, whereas laser action disappears because of the increasing refraction and collision thermalisation of laser levels. The electron density and spontaneous emission of the plasma achieve a maximum at the stagnation instant, 5–8 ns after the laser pulse.

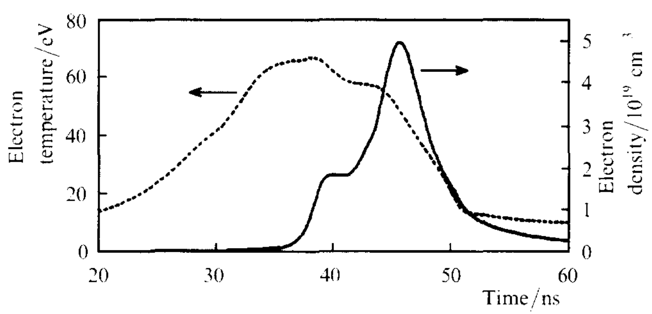

Figure 6. Calculated behaviour of the electron density and temperature at the capillary-discharge axis.

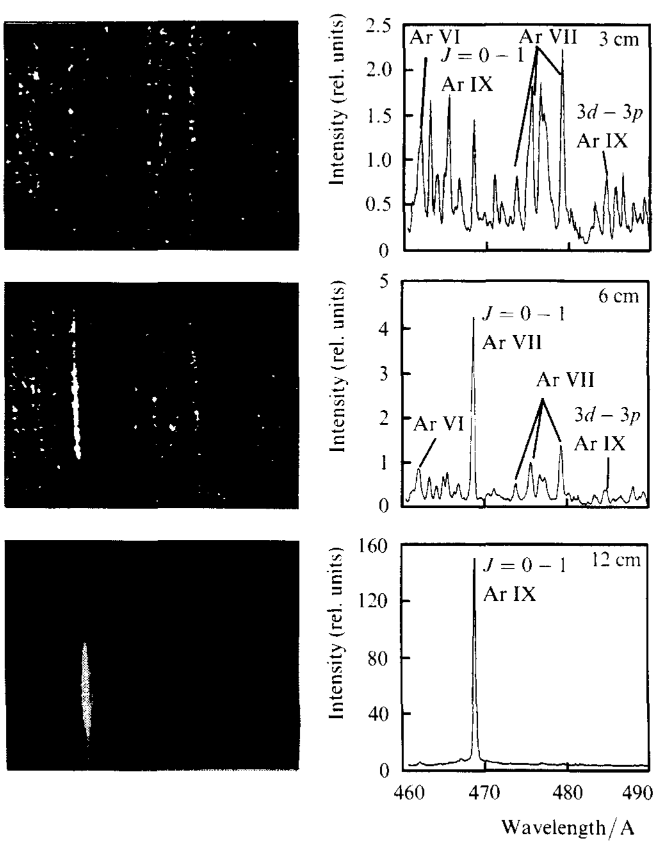

Figure 7. Spectra observed along the capillary-discharge axis. The increase in the 469-A line intensity with increasing the capillary length from 3 to 12 cm clearly demonstrates laser action.

4. Lasing at 469 Å

Laser action in the X-ray range in an electric discharge was first observed by Rocca and co-workers in 1994 on the $3p - 3s$ transition ($J = 0 \rightarrow J = 1$) in the Ne-like argon ion at 469 Å [58]. The authors of [58] used a fast capillary discharge (see Fig. 2). The duration of the first half-period of the discharge current was 60 ns, the peak current was 40 kA, the capillary diameter was 4 mm, and its length was up to 12 cm. Fig. 7 shows the dependence of the lasing line intensity on the capillary length. From these data, using the Linford formula [59], the maximum gain $gL = 7.2$ was determined. Simultaneously, a weak amplification at a wavelength of 698 Å corresponding to the $3p - 3s$ transition ($J = 0 \rightarrow J = 1$) in the same ion was observed [43].

In the subsequent experiments, capillaries of length up to 20 cm were used, and the discharge conditions were optimised. Double-pass amplification experiments performed with an iridium mirror [36] gave $gL = 27$. Thus, saturation was achieved in the X-ray range for the first time.

The results of single-pass amplification experiments with a capillary laser of length up to 15.8 cm are shown in Fig. 8. One can see that the laser pulse energy increases exponentially with the laser length approximately up to 12 cm and then begins to saturate. The processing of these data with the help of the Linford formula gives the gain equal to 1.16 cm^{-1}; the laser output begins to saturate for $gL = 14$. These results agree with two independent numerical models of a plasma column in the capillary. The solid curve in Fig. 8 corresponds to the calculations assuming that the profiles of the electron density and the gain are parabolic. The dashed curve corresponds to the electron density and the gain obtained from numerical models in which magneto–hydrodynamic motion and nonstationary atomic processes were taken into account [36]. These calculations showed that the consideration of refraction losses provides an adequate description of the experimental parameters of the plasma. The duration of the coherent X-ray pulse was 0.8 ns [36].

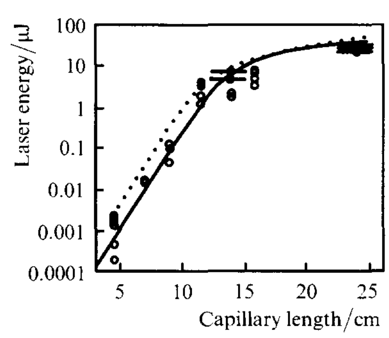

Figure 8. Dependence of the lasing energy on the capillary length: comparison of calculations (horizontal bars) with experiment (circles).

The obtained results allowed the development of compact 469-Å lasers with dimensions close to those of typical visible and UV gas lasers [54, 60, 61]. Fig. 3 shows such an X-ray laser together with a 5-mW helium-neon laser shown for comparison. A compact capillary discharge laser occupies an optical table space of 1m by 0.4 m [61]. These lasers were successfully used in interferometry and schlieren photography of plasmas [62, 63]. A laser of almost the

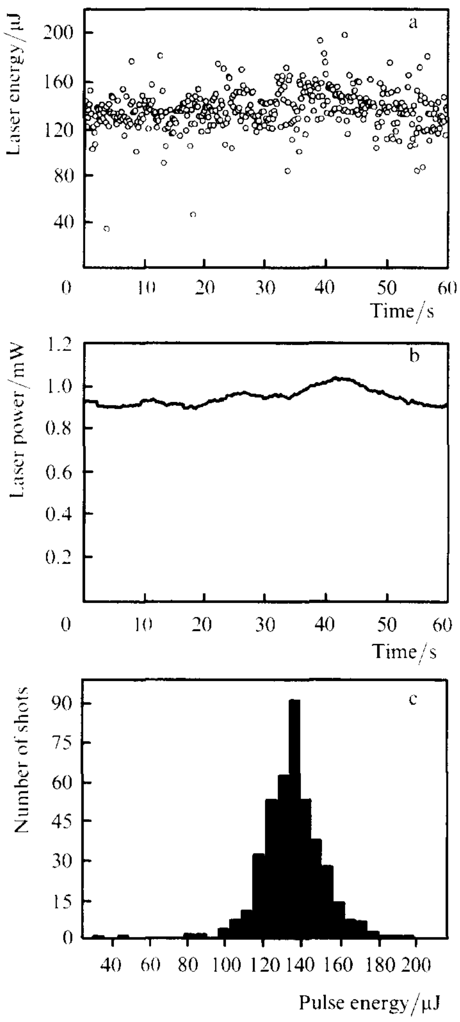

Figure 9. Energy characteristics of the 469-Å laser with a pulse repetition rate of 4 Hz: time dependence of the pulse energy (a), the pulse power averaged over 60 shots (b), and the energy distribution of pulses (c).

same size produced 135 µJ per pulse at a repetition rate of 7 Hz, which corresponds to an average power of 0.9 mW. Later, the energy power was increased up to 0.88 mJ at a pule repetition rate of 4 Hz [54]. Fig. 9 shows the output energy and average power of this laser, in which a ceramic capillary of length 34.5 cm is used. The coherent properties and spectral brightness of the beam of this laser emitting at 26.5 eV is similar to those of the beams produced by synchrotron sources of the third generation [60].

The parameters and applications of a repetitively pulsed capillary discharge X-ray laser are discussed below. Here, we note in conclusion that, along with argon, lasing was also obtained in sulphur vapour and chlorine at the wavelengths 608 and 529 Å of transitions in the Ne-like ions, respectively [64].

5. Characteristics of the beam of a capillary discharge X-ray laser

The divergence and the near- and far-field intensity distributions of radiation of a capillary X-ray laser were systematically studied under various discharge conditions [61]. Fig. 10 shows the evolution of the near- and far-field intensity distributions for different pressures of argon in a polyacetate capillary of length 4 mm. When the pressure was changed from 750 to 500 mTorr, the beam diameter at the amplifier output and its divergence increased from 150 to 300 µm and from 2 to 5 mrad, respectively. The laser spot changed simultaneously from a uniform spot to a circular one. This is explained by refraction in low-pressure capillaries caused by large gradients of the electron density [61]. Large gradients appear, as a rule, in plasma filaments of a small diameter due to a strong compression. The radiation intensity distribution in capillary lasers at high pressures has a good cylindrical symmetry. The spatial structure of radiation, typical of X-ray lasers excited by visible lasers [65], was not observed in this case.

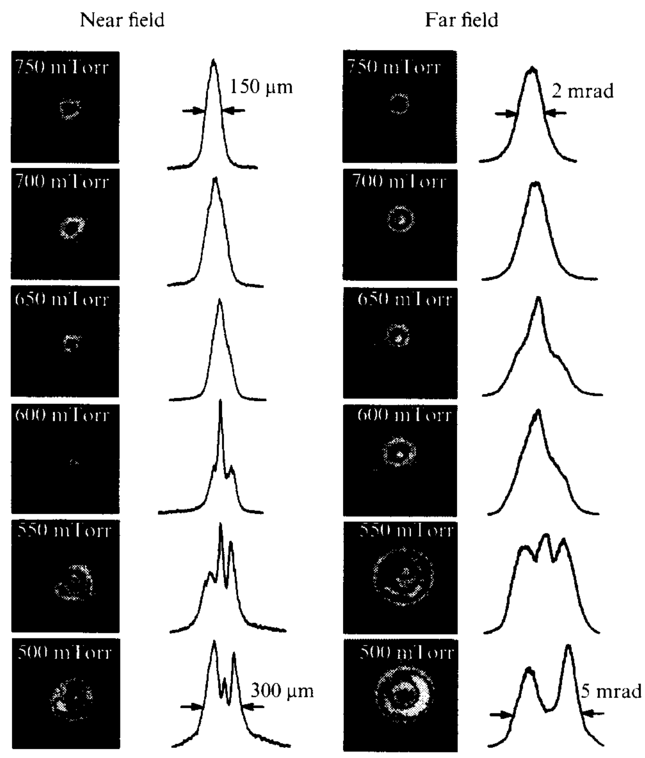

Figure 10. Near- and far-field radiation intensity distributions for the X-ray laser at argon pressures varied from 500 to 750 mTorr.

Another important characteristic of the laser beam is its spatial coherence. The measurements showed for the first time a monotonic increase in the spatial coherence with the capillary length [66]. This result is very important for achieving the high degree of coherence in cavityless X-ray lasers. As was predicted in [67, 68], the spatial coherence increases due to a simultaneous action of the waveguide effect and defocusing, which reduce the number of modes captured by a plasma column. The spatial coherence of radiation from a capillary Ne-like argon ion laser was measured by introducing a knife diaphragm into the laser beam (Fig. 11). This method was developed by Rus and was first used by Albert *et al.* in measurements of the coherence of radiation from a Ne-like zinc ion laser [69]. Fig. 11 shows the radiation divergence measured for capillaries of lengths from 8 to 16.4 cm and the corresponding theoretical calculations. As the amplifier length is increased, the visibility of diffraction fringes improves. Fig. 11 shows the results of quantitative analysis of these data. The

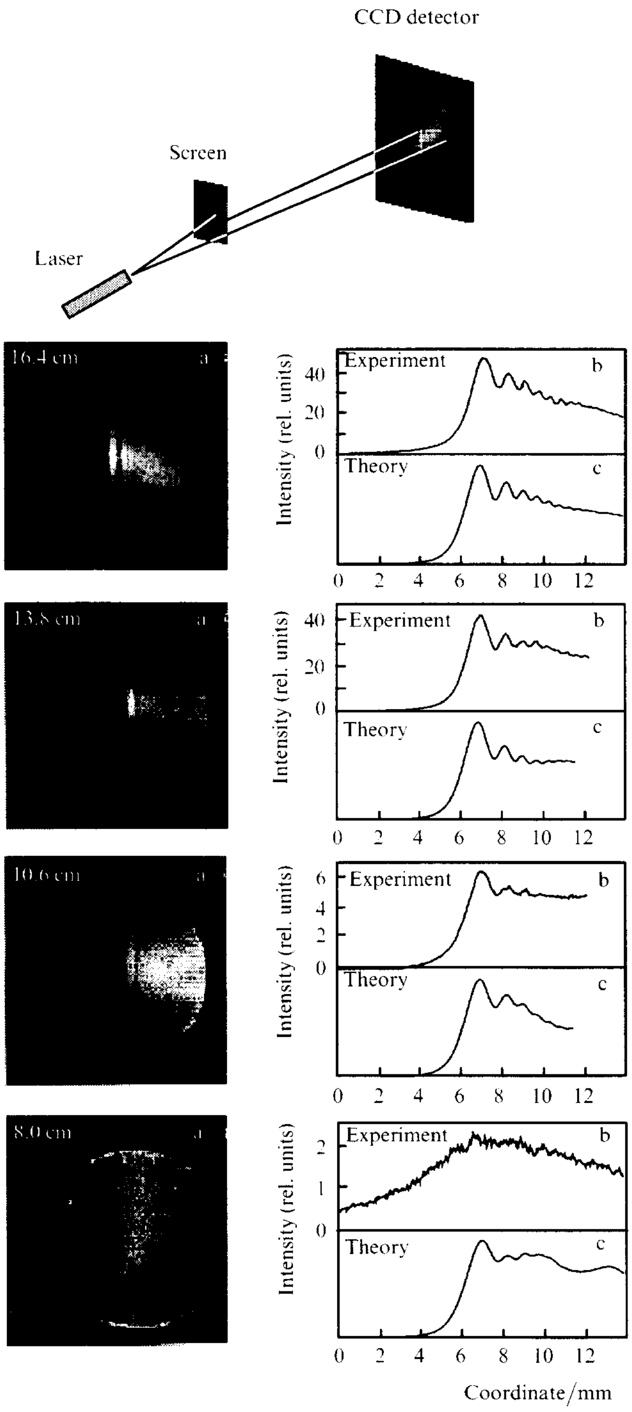

Figure 11. Scheme and the results of measurements of the spatial coherence of the capillary discharge laser. At the left: (a) diffraction patterns obtained for different capillary lengths; at the right: results of the pattern processing (b) and simulations (c).

coherence length for a capillary of length 16.4 cm was of about 4.5 mm in the plane located at a distance of 5.9 m from the output window of the amplifier. This corresponds to the effective coherence angle of 0.8 mrad, which exceeds the diffraction-limited divergence by a factor of six. The monotonic increase in the spatial coherence with the capillary length also confirms the high axial homogeneity of the plasma produced in fast capillary discharges.

6. Applications of a capillary discharge X-ray laser

A capillary discharge laser is one of the brightest X-ray sources available now. The main parameters of the capillary discharge Ne-like Ar laser operating on the $3p-3s$ transition are listed below.

Wavelength/Å	469
Pulse energy/mJ	0.1–0.9
Pulse duration/ns	0.6–1.5
Average power/mW	3.5
Peak power/MW	0.1–0.6
Linewidth/$\Delta\lambda/\lambda$	less than 10^{-4}
Divergence/mrad	4–6
Overall efficiency (%)	$10^{-3}-10^{-4}$
Operating life (without capillary replacement)/pulses	$(3-8)\times 10^3$
Dimensions/m	$0.4\times 0.4\times 1$

Thus, the average output power in the laser line (~ 3 mW) is much higher than that of monochromatic radiation beams obtained usually in synchrotrons. The peak spectral brightness, i.e., the number of photons per mm^2 emitted within a solid angle of 10^{-6} mrad^2 is 2×10^{25} photon mm^{-2} mrad^{-2} into the band $\Delta\lambda/\lambda=0.01$ %. This value is a few orders of magnitude greater than that obtained in specialised third-generation synchrotrons, and probably will be surpassed only in free electron lasers [60].

The coherence radius of the laser spot at a distance of 15.7 cm from the laser is 0.55 mm. This spot contains from 12.5 % to 50 % of the pulse energy. Unlike a synchrotron, the wavelength of a capillary laser cannot be tuned. For this reason, despite the high average and peak power, the capillary laser is not an alternative to synchrotron radiation in a variety of its applications. At the same time, a number of experiments have already been performed which show that a compact capillary discharge laser opens up new possibilities and can be used in studies of high-temperature dense plasmas, the ablation and modification of materials, in reflectometry and ellipsometry, and for calibrating optical elements. In [70, 71], the development of multilayer coatings based on reflecting periodic Sc–Si structures was reported. These coatings allow the fabrication of mirrors with the reflectivity of 45 % for normal incidence, as well as polarising mirrors at the angle of incidence close to 45°.

Thus, a compact quasi-continuous source of laser radiation appeared for the first time at the disposal of researchers, and the efficient optics for controlling the laser beam was developed.

One of the first applications of this laser was the interferometry of dense high-temperature plasmas produced in fast discharges. The advantages of radiation from the X-ray laser compared to the 265-nm fourth harmonic of a neodymium laser, which is often used for this purpose, are obvious. First, because the emission wavelength of the X-ray laser is shorter, the critical plasma density, i.e., the maximum density of the plasma to which radiation can penetrate increases by a factor of 32, amounting to $\sim 3\times 10^{22}$ cm^{-3}. Second, the mean free path of probe radiation, which is determined by bremsstrahlung absorption, also increases. For example, for a plasma with the electron concentration n_e, the electron temperature of 200 eV, and the average charge $Z = 15$, the attenuation of the laser beam by a factor of e along the path l corresponds to the product

$$n_e^2 l = 5.8 \times 10^{41}\ \text{cm}^{-5},$$

whereas for the fourth harmonic of the Nd:YAG laser,

$$n_e^2 l = 1.7 \times 10^{40}\ \text{cm}^{-5}.$$

This means that for $n_e = 2 \times 10^{21}$ cm^{-3}, the characteristic size of the plasma studied increases from 40 μm up to 1.5 mm.

Schlieren photographs and interference patterns of the micropinch plasma with temperature ~ 10 eV were obtained with the help of a capillary discharge laser in papers [72, 73]. The maximum value of n_e obtained after processing of the interference patterns was 3×10^{19} cm^{-3}. The interference fringes were obtained using a Lloyd interferometer with two multilayer mirrors.

In [74], laser plasma was probed with a capillary laser in the Mach–Zehnder interferometer scheme. The laser beams were separated and combined using grazing diffraction gratings. The interference fringes were localised with the help of a spherical multilayer mirror. The maximum electron density was ~ 10^{20} cm^{-3} [75]. The estimates show that the fourth harmonic of the Nd:YAG laser cannot be transmitted by such a dense and inhomogeneous plasma because of refraction.

The high average power of a capillary discharge X-ray laser allows one to use it in reflectometry and ellipsometry. For this purpose, a reflectometer was assembled based on a compact capillary laser for measuring the reflectivity and determining from these data the optical constants n and κ at 469 Å. Similar measurements were performed earlier only with the help of synchrotrons or at the wavelengths 584 and 304 Å using a helium lamp. The results of measurements performed with the laser reflectometer are reported in [76]. Note that the depth of radiation penetration into any materials in this spectral region is extremely small and does not exceed 10 nm. The contamination of a sample surface in the atmosphere further reduces the radiation penetration depth and strongly affects the reflectivity. The preparation of samples with a clean surface, which does not change the reflectivity, is an extremely complicated problem. This problem is solved by performing measurements at many different angles of incidence and fitting the experimental values of n and κ by their theoretical values calculated with the help of models taking into account the presence of a contaminated intermediate layer, whose parameters are determined from the same measurements (see details in [15] and [76]). Because the average power of the capillary laser is high, such measurements performed with a laser reflectometer do not require much time and provide a sufficiently high accuracy of measurement of the optical constants. The measurements were performed for Si, SiO_2, GaAs, GaP, GaAsP, and Ir. The optical constants of some of these materials were not known in this spectral region.

The same laser reflectometer was used for polarisation measurements of the efficiency of diffraction gratings [77]. After two reflections from multilayer mirrors at an angle of 45°, the laser beam acquired the degree of linear polarisation equal to 96 %. The limiting possibilities of the Sc–Si multilayer mirrors used for manufacturing various polarisation elements were considered in [78].

The high pulse energy of the capillary discharge laser and the presence of mirrors made it possible to produce intense radiation fluxes and to study the ablation of materials for the first time in this spectral range [79]. The X-ray laser beam was sharply focused using a scheme containing a flat and a concave multilayer mirrors. As a result, craters of diameter ~ 17 μm with deep holes of diameter up to 3 μm at the centre were produced on the surfaces of brass, copper, and stainless steel. A comparison with the calculated distribution of the laser radiation intensity on the sample surface gave the maximum intensity ~ 10^{11} W cm^{-2}. Thus, the repetitively pulsed X-ray laser provides the radiation intensity on the sample surface that is sufficient for the modification and processing of materials, and for their ablation.

7. Conclusions

The development and scientific applications of the first repetitively pulsed X-ray laser is an important step in the solution of the problem of mastering the X-ray spectral range, which was already formulated at the advent of quantum electronics. As mentioned above, the difficulties arising with decreasing the lasing wavelength in a plasma active medium not only involve technological problems but also have a fundamental nature. Therefore, it is difficult to predict now whether the shorter-wavelength compact X-ray lasers will be created using a capillary discharge.

At the same time, a number of related problems have been solved during the studies devoted to the development of laboratory X-ray lasers. (The results of X-ray laser studies are analysed in detail by J. Nilsen [80–82] at the Lawrence Livermore National Laboratory, USA.) Note first of all the development of fast electric discharges initiating a homogeneous plasma filament of length a few tens of centimetres with an aspect ratio of 1000 : 1; the spatial and temporal control of pump laser pulses, which allows one to obtain the plasma parameters in the active medium that can provide a high gain in the X-ray spectral region; and the development of new methods and means for plasma diagnostics and spectroscopy. A great progress has been achieved in the wavelength measurements and calculations of the radiation transition probabilities and other fundamental characteristics of multiply charged ions. Investigations on X-ray optics were closely related to the works on X-ray lasers.

At present, it is hoped that free electron lasers will provide a further substantial advancement to the short-wavelength X-ray range. These large-scale and expensive facilities are only being built now, whereas the capillary discharge laser already has the parameters that allow one to perform experiments with the record high pulsed and average power of coherent X-ray beams. Therefore, along with its own applications, the capillary discharge laser gives the opportunity to researchers to acquire the knowledge and experience that are useful for the development and applications of the future X-ray lasers. Interest in the capillary discharge laser has increased in recent years [83–86]. This laser has become the object of a long-standing collaboration between researchers at the Colorado State University and the N.G. Basov Department of Quantum Radiophysics at

P.N. Lebedev Physics Institute, RAS. Within the framework of this collaboration supported by the CRDF Foundation (Grant Nos RP-240 and RP1-2267), multilayer optics was developed for the capillary discharge laser and the studies on its applications are continued.

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