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Development, production, and application of sealed-off copper and gold vapour lasers

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Abstract. **An analysis is made of the current state of the art of scientific and engineering advances in the field of repetitively pulsed self-heating metal vapour (copper and gold) lasers based on industrial, sealed-off, high-temperature, metal–ceramic and metal–glass active elements. The major applications of these lasers are discussed. The energy, spatial, and time characteristics of the lasers and their dependence on the parameters and construction of the laser active elements (tubes) and optical resonators are considered. The ways for the development of new high-power industrial laser active elements with a high efficiency (1 – 2 %) and a service life of 500 – 1000 h are analysed. An average output power of 80 W was realised with a laser tube 150 cm in length and 32 mm in diameter. When the pumping efficiency is improved by raising the voltage to 30 – 35 kV, this system in a copper vapour laser will allow an output power of 100 W to be obtained with one active element. The characteristics of industrial versions of metal vapour lasers manufactured in different countries are compared and discussed.**

Keywords: *self-heating lasers, repetitively pulsed lasers, oscillator–amplifier system, unstable resonator, industrial lasers.*

1. Introduction

35 years have passed since the time when lasing was first obtained on self-terminating transitions of metal atoms in 1965 [1 – 3]. By the time of writing this paper, the basic design principles of copper vapour lasers (CVLs) were determined and the studies of the physical processes that occur in their active media and determine their basic characteristics were close to completion [4 – 9]. At present this situation favours broad applications of these lasers and the use of new possibilities offered by them [8, 9]. All this attracts interest in the development of industrial metal vapour lasers. A retrospective glance at the history of metal vapour lasers shows that Refs [4, 5, 10 – 13] had a profound impact on the strategy and the tactics of research in the early stage of the development of such lasers. Several ways and systems of excitation have been realised to date: by longitudinal and transverse discharges, in a hollow cathode and by an electron beam, gas-dynamic, gas-flow, and explosion systems, etc. A CVL is a prominent example of such lasers. It is the highest-power and highest-efficiency laser in the visible spectral region. A single active element (AE) in this laser is capable of delivering an average output power of 100 – 750 W at an efficiency of 1 – 3 % [8, 9].

Work to produce industrial metal vapour lasers commenced with the start-up of the first self-heating CVL [11, 14] and practically dates back to 1971. In several succeeding years, the first USSR industrial versions of sealed-off self-heating metal vapour lasers were developed and produced in the 'Istok' State Scientific and Industrial Enterprise (SSIE) in cooperation with the P N Lebedev Physics Institute [15 – 17]. Below, we present a review of commercial sealed-off copper and gold vapour lasers produced in the 'Istok' SSIE as the result of research and engineering work. We describe complex studies aimed at improving the efficiency, the output power, the quality of radiation, and the service life of these lasers, and their principal applications.

One important application of a CVL is the laser isotope separation of different atoms by the AVLIS technique based on the difference in the absorption spectra of different atomic isotopes. The AVLIS technology uses tunable dye lasers pumped by CVLs. These technologies are discussed in detail in Refs [8, 9, 18, 19]. Another rapidly progressing field is the so-called optical systems with image intensifiers [20]. These systems employ the active media of copper, gold, barium, and other vapour lasers as image intensifiers [21 – 30].

As would be expected, precision metal processing occupies a remarkable place among the CVL applications [24]. Copper and gold vapour lasers – both individually and in combination with tunable dye lasers – find wide applications in medicine. Of special significance is their use for the treatment of malignant tumours by the photodynamic therapy method [31 – 35]. Another successful application of these lasers is the treatment of vascular skin defects, the so-called port-wine stainss, gemangiomas, angiomas, and also pigmentary defects [32].

Metal vapour lasers in a combination with dye lasers, which produce high-power efficient (20 – 30 %) tunable emission in the visible and near-IR spectral ranges, are widely used for spectroscopic research. With the aid of nonlinear crystals it is possible to convert with high efficienvy (~ 10 %) the CVL radiation to the second harmonic, i.e., to

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Table 1. Main technical parameters of the 'Kulon' AEs.

AE model	Laser	Laser medium	p_{Ne}/Torr	λ/nm	P_{rad}/W		$P_{510.6} : P_{578.2}$	f_{opt}/kHz	Range f/ kHz
					power supply I	power supply I			
LT-1Cu	GL-206A	copper	600	510.5; 578.2	–	1.2 – 1.4	3:2	15 – 18	8 – 25
LT-1.5Cu	GL-206B	copper	600	510.5; 578.2	–	1.5 – 2.0	3:2	15 – 18	8 – 25
LT-3Cu	GL-206V	copper	450	510.5; 578.2	6	3.5 – 4.0	3.5:2	14 – 17	8 – 17
LT-5Cu	GL-206G	copper	300	510.5; 578.2	9	5 – 7	3.5:2	14 – 17	8 – 17
LT-6Cu	UL-102	copper	300	510.5; 578.2	15	6 – 8	5:3	10 – 12	8 – 14
LT-10Cu	GL-206D	copper	300	510.5; 578.2	15	10 – 11	3:2	14 – 17	8 – 17
LT-1Au	GL-206E	gold	300	627.8	1.3	–	–	14 – 17	10 – 17
LT-1.5Au	GL-206Zh	gold	300	627.8	1.8	–	–	14 – 17	10 – 17

Notes: p_{Ne} is the pressure of the buffer neon gas; λ is the laser wavelength; P_{rad} is the average total output power (for an optimal pulse repetition capacitance of the storage capacitor $C_s = 1500$ pF (Fig. 3a); $P_{510.6}$ and $P_{578.2}$ are the respective output powers at $\lambda = 510.6$ and 578.2 nm; f is the pulse active medium; τ_1 is the readiness time (for a nominal power consumption); P_{rec} is the power consumption; Q is the guaranteed service life; (PR) plane-

Table 2. Main technical parameters of the 'Kristall' AEs.

AE model	Laser	Laser medium	p_{Ne}/Torr	λ/nm	P_{rad}/W		$P_{510.6} : P_{578.2}$	f_{opt}/kHz	Range f/ kHz
					lasing mode*	amplification mode*			
LT-30Cu	GL-205A	copper	250	510.6; 578.2	30 – 32	40 – 45	1:1	10 – 12	8 – 20
LT-40Cu	GL-205B	copper	180	510.6; 578.2	39 – 41	55 – 60	1:1	10 – 12	8 – 20
LT-50Cu	GL-205V	copper	150	510.6; 578.2	47 – 50	65 – 70	3:2	10 – 12	8 – 20
LT-4Au	GL-205G	gold	200	627.8	4 – 6	–	–	14 – 17	10 – 20

*Powered by a thyratron modulator with voltage doubling (Fig. 3b).

UV radiation, with an average output power of 1 – 9 W. The CVL radiation is also used to pump $Ti^{3+}:Al_2O_3$ lasers to obtain tunable lasing in the near-IR spectral region and in the blue spectral region upon frequency doubling [36]. Such multifrequency repetitively pulsed tunable laser systems with a high average output power are unique.

In addition, these lasers and the instruments on their basis have been used for years for atmospheric research [37], the studies of Raman light scattering, image conversion, phase conjugation, gene engineering, high-speed photography and holography, holographic cinema, spectroscopic and mass spectroscopic investigations, gas flow visualisation, laser acceleration of microparticles, astronomical research, projection microscopy, cinema and television, navigation and monitoring, ultrashort-pulse amplification, etc. [8, 9].

The progress of research in these fields has been recently discussed at numerous all-Russian and International Conferences ['Metal Vapour Lasers' (Novorossiisk, 1998, Lazarevskoe, 2000), LASER's (USA, 1998, Canada, 1999), 'Pulsed Lasers on Atomic and Molecular Transitions' (Tomsk, 1997, 1999), and others], which is beneficial for maintaining a stable interest in these lasers on the part of both scientific institutions and industrial enterprises.

Lasers manufactured at the 'Istok' SSIE are delivered to leading research and industrial organisations in Russia as well as to several FSU and foreign countries. In Russia, the customers are the Kurchatov Institute Russian Research Centre and the 'Altek' Co. (Moscow); the 'Lad' (Khimki) and 'Latra' (Troitsk, Moscow Oblast) Research and Production Associations; the Institute of Semiconductor Physics (Novosibirsk); the Research Institute of Electrophysical Equipment (St. Petersburg) and the St. Petersburg State Technical University; the P N Lebedev Physics Institute, the General Physics Institute, and the Institute of High Temperatures (Moscow); the Institute of Spectroscopy (Troitsk, Moscow Oblast); the Institute of Atmospheric Optics, Siberian Division, Russian Academy of Sciences (Tomsk) and the Tomsk State University; and other organisations.

During the past three years, the 'Istok' SSIE modernised its productive and technological basis and increased the number of devices manufactured. The average annual sales of laser active elements amount to 70 – 100.

2. Design and main parameters of the copper and gold vapour laser AEs of the 'Kulon' and 'Kristall' series

In 1998, the 'Istok' SSIE completed the development and launched the production of new models of highly efficient commercial sealed-off self-heating AEs for metal vapour lasers of the 'Kulon' series with an average output power from 1 to 15 W [GL206 (A, B, V, G, D, E, Zh)] and the 'Kristall' series with an output power from 20 to 50 W [GL-205 (A, B, V, G)] [38 – 45]. At present, work is underway to refine the lasers of this class with the aim to improve their reliability and quality and also to raise the output power of a single AE to 100 W and over.

The main technical parameters of new AE models of the 'Kulon' series are presented in Table 1 and of the 'Kristall' series in Table 2, the overall and connection dimensions and the mass are given in Fig. 1 and Table 3, the appearance is shown in Fig. 2, and the excitation schemes are diagrammed in Fig. 3. The outdated models TLG-5 (1975), UL-101 (1976), UL-102, GL-201, and GL-202 (1982), and GL-204 (1986) differ from the new ones primarily by the higher power consumption, the lower efficiency and the lower service life.

An AE represents a cylindrical vacuum-tight dielectric body with terminal glass sections and sealed-in optical windows for laser radiation coupling. To eliminate the parasitic coupling of the output windows to the active medium, the angle between the window plane and the optical axis of the device is 76 – 78 °.

τ/ns	d/mm	L/mm	V/cm^3	Divergence/mrad		τ_1/min	P_{rec}/kW	Q/h
				PR	UR			
10–15	7	140	4.2	6	0.3	25	0.65	1000
10–15	7	175	5.7	5.5	0.3	25	0.75	1000
17–20	12	340	28	6	0.3	45	1.15	1000
17–20	14	340	38	6.5	0.3	50	1.2–1.5	1000
20–25	20	470	116	7	0.3	50	1.7–2.1	500
17–20	14	490	65	4.5	0.3	50	1.5–1.8	1000
15–18	14	340	38	6	0.3	50	1.4	500
15–18	14	490	65	4	0.3	60	1.9	500

rate); power supply I is powered by a thyratron modulator with voltage doubling (Fig. 3b); power supply II is powered by a thyratron modulator with a repetition rate; τ is the output pulse duration; d is the diameter of the discharge channel; L is the length of the discharge channel; V is the volume of the parallel resonator; (UR) unstable resonator.

τ/ns	d/mm	L/mm	V/cm^3	Divergence/mrad		τ_1/min	P_{rec}/kW	Q/h
				PR	UR			
10–20	20	900	250	4	0.1–0.5	60	2.9–3.1	1000
10–20	20	1200	350	3	0.1–0.5	60	3.6–3.9	1000
20–30	32	1200	900	5	0.1–0.5	80	4.3–4.7	500
10–20	20	900	250	4	0.1–0.5	60	3.5–3.8	500

Table 3. AE parameters (see Fig. 1).

Model	L_1/mm	L_2/mm	d_1/mm	d_2/mm	a/mm	Mass/kg
LT-1Cu	330	145	84	55	14	1
LT-1.5Cu	380	185	84	55	14	1
LT-3Cu	600	318	100	73	14	2.4
LT-5Cu	600	318	100	73	14	2.6
LT-6Cu	770	480	140	90	19	5
LT-10Cu	770	495	100	73	14	3.3
LT-1Au	600	485	100	73	14	2.6
LT-30Cu	1315	916	134	90.5	19	11
LT-40Cu	1621	1222	134	90.5	19	13.5
LT-50Cu	1627	1227	134	90.5	19	15
LT-4Au	1313	916	134	90.5	19	11

The discharge channel consists of a set of ceramic tubes connected by sleeves. The percentage of aluminium oxide Al_2O_3 is 99.8 % [46]. At the junctions are located the generators of the active material – a metal vapour. A tungsten–barium cathode ensures a high degree of localisation and stability of the pulsed arc discharge. At the ends of the discharge channel, the traps are placed to protect the output windows, primarily from the vapour of the active material and particles ejected from the working segments of the cathode and anode. A strong heat-insulation layer located between the discharge channel and the vacuum-tight shell ensures high operating temperatures of the discharge channel (1500 – 1700 °C) for a moderate power consumption (0.5 – 4.7 kW). High-purity neon is used as the buffer gas.

Small-size (0.77 m and shorter) AEs of the 'Kulon' series, which have low electric power requirements (2.1 kW and below), have primarily a metal-glass vacuum-tight shell (body) and are operated in the air cooling regime. In contrast, the AEs of the 'Kristall' series are approximately two times longer (about 1.5 m), weigh up to 15 kg, consume a power up to 4.7 kW, are primarily manufactured of metal ceramics, and require a water cooling. In this case, the AE is mounted inside a water-cooled jacket of cylindrical or rectangular shape requiring a water flow rate up to 5 litre min^{-1}. The jacket usually fulfils the role of a reverse current carrier.

The AE parameters presented in Tables 1 and 2 were obtained and optimised primarily using capacitive voltage doubling and a magnetic compression link (Fig. 3b) [47, 48].

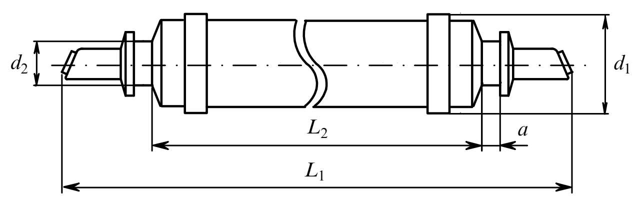

Figure 1. Schematic of AE (see Table 3).

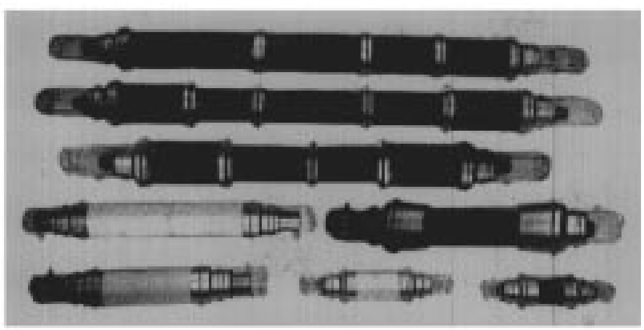

Figure 2. Appearance of active elements.

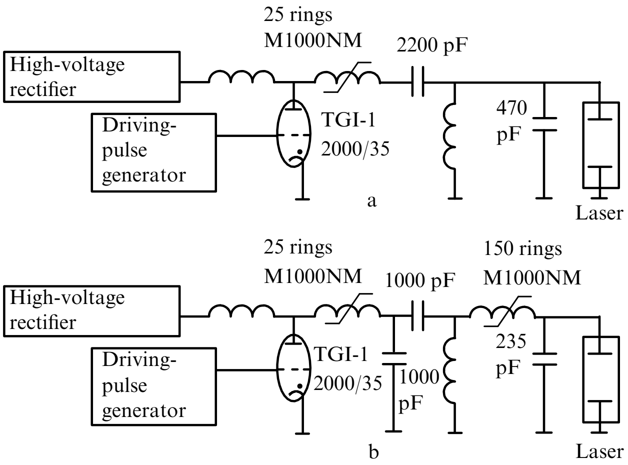

Figure 3. Circuits of the pulsed power supply.

In the 'Kristall' AEs where the volume of the active medium is one to two order of magnitude larger than in the 'Kulon' AEs, the employment of a voltage doubling scheme allowed an increase in output power up to a factor of two. By the specific characteristics attained in the stationary regime, the commercial sealed-off AEs developed by the 'Istok' SSIE are superior to the known Russian and foreign analogues.

3. Results of investigations of the CVL AEs of the 'Kristall' series (LT-30Cu, LT-40Cu, LT-50Cu)

3.1. Traditional excitation circuit

Fig. 4a shows the experimental characteristics of the LT-30Cu 'Kristall' AE for a traditional excitation circuit (Fig. 3a) as functions of the power P_{rec} extracted from the rectifier; the characteristics were obtained in the steady-state thermal regime for a pulse repetition rate $f = 10$ kHz, a neon buffer gas pressure $p_{Ne} = 150$ Torr, a capacitance of the storage capacitor $C_s = 2200$ pF, and a capacitance of the peaking capacitor $C_{peak} = 470$ pF. One can see from the curves that lasing appears for a temperature of the discharge channel $T \sim 1300$°C ($P_{rec} = 1.6$ kW), i.e., for a copper atom concentration $n = 7 \times 10^{13}$ cm^{-3} ($p_{Cu} \approx 0.01$ Torr) [49]. The maximum output power equal to 20 W (curve *1* in Fig. 4a) is reached for a temperature $T = 1550$°C ($P_{rec} = 2.7$ kW) to which $n = 2 \times 10^{15}$ cm^{-3} ($p_{Cu} \approx 0.35$ Torr) corresponds. The output power in individual wavelengths also is maximum at this temperature: 11 W (55 %) at 0.51 μm and 9 W (45 %) at 0.58 μm.

As the temperature is increased above 1550 °C, the output power decreases, this decrease being much steeper for the green line (0.51 μm, curve *2* in Fig. 4a) than for the yellow one (curve *3*). This may be explained by the fact that the lower (metastable) level is located higher for the yellow line than for the green one and is accordingly less prone to thermal population. A complete quenching of lasing on the green line takes place for a temperature of the discharge channel $T \sim 1650$°C ($P_{rec} = 3.2$ kW) and for $T = 1700$°C ($P_{rec} = 3.4$ kW) on the yellow one.

To illustrate the efficiency of the circuit under discussion, Fig. 4a (curves *6–8*) shows the oscilloscope traces of the voltage, current, and radiation pulses in the optimal thermal AE regime – the regime of maximum output power. The duration of current pulses (at the base) was ~ 300 ns, which is approximately 7 times longer than the laser pulse duration (curve *8*), i.e., virtually than the inversion lifetime.

That is why a highly efficient laser operation could not be expected with the use of a 'traditional' excitation circuit – the peak efficiency in the power extracted from the rectifier was only ~ 0.75%.

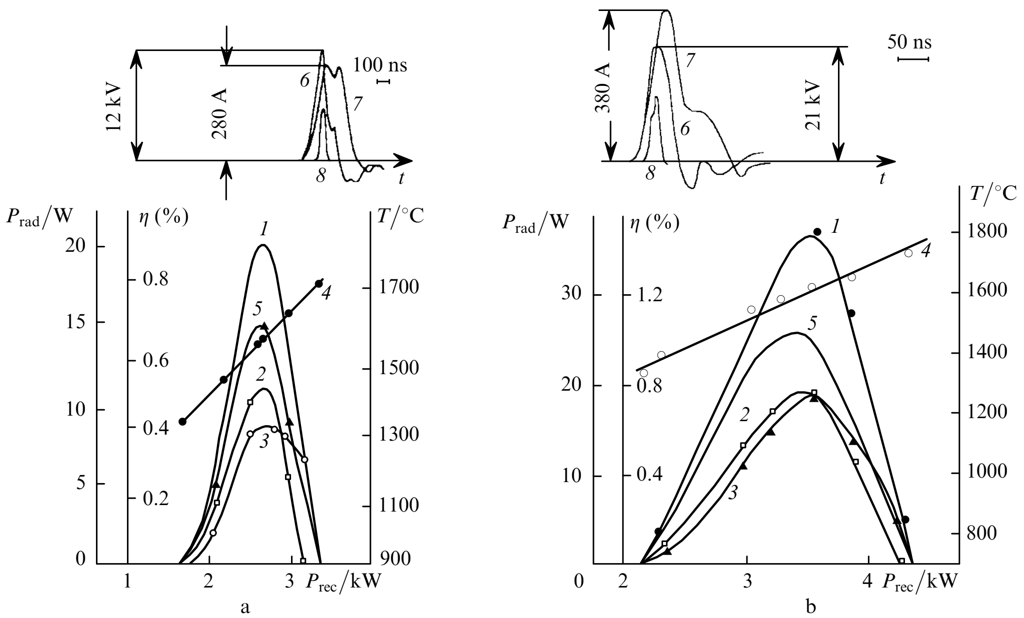

Figure 4. Dependences of the total average output power P_{rad} (*1*), output power at the 0.51 (*2*) and 0.58 μm (*3*) wavelengths, the temperature of the AE discharge channel (*4*), and the efficiency η (*5*) on the power extracted by an LT-30Cu 'Kristall' AE from the rectifier for a traditional excitation scheme (a) and a voltage doubling scheme (b), and also oscilloscope traces of the voltage (*6*), the discharge current (*7*), and the laser pulses (*8*) of the AE.

3.2. Excitation circuit with a capacitive voltage doubling and a magnetic compression link

With the use of a voltage-doubling circuit (see Fig. 3b), the duration of excitation pulses shortens by about a factor of two compared to that obtained with the traditional circuit. Fig. 4b shows the energy laser characteristics in steady-state thermal regimes as functions of the power extracted from the rectifier. Also shown are the oscilloscope traces of excitation pulses in the regime of peak output power (optimal thermal regime) for a pulse repetition rate $f = 10$ kHz, a capacitance of the storage capacitor $C_s = 1000$ pF + 1000 pF = 2000 pF, a capacitance of the peaking capacitor $C_{peak} = 235$ pF, and a neon pressure $p_{Ne} = 150$ Torr. The duration of a voltage pulse (curve *6*) was about 100 ns for an amplitude of 21 kV and the duration of a current pulse (curve *7*) was 160 ns for an amplitude of 380 A.

With the circuit of Fig. 3b, lasing occurs, like with a traditional circuit, for a temperature of the discharge channel $T \sim 1300$°C (curve *4* in Fig. 4b) ($P_{rec} = 2.2$ kW). The peak output power (37 W) and efficiency (~ 1%) (curve *5*) are reached for a temperature 80 °C higher, i.e., for $T = 1630$°C ($P_{rec} = 3.6$ kW). At this temperature, the pressure and the density of copper atoms are 0.85 Torr and 5×10^{15} cm^{-3}, respectively [49]. Therefore, in the lasing regime a two-fold compression of excitation pulses results in a 1.8-fold rise of output power (for $p_{Ne} = 150$ Torr and $C_s = 2200$ pF) and a 1.4-fold increase in efficiency relative to the rectifier. In this case, the output powers at individual wavelengths (curves *2* and *3*) are not only maximised, but are approximately equal as well. The temperature $T = 1750$ °C corresponds to the quenching of lasing at the green line (curve *2*) and the temperature $T = 1800$ °C corresponds to the quenching of lasing at the yellow line.

3.3. Dependence of the output power and the efficiency on the energy consumption in the lasing regime

To estimate the feasibility of a further increase in the efficiency, a study was made of the 'instantaneous' average output power P_{rad} as a function of the energy consumption for a constant temperature of the discharge channel with an excitation circuit of Fig. 3b. The experiment involved an abrupt change of the rectifier power upon removing from the optimal operating point ($P_{rec} = 3.6$ kW, $T = 1630$°C, $P_{rad} = 37$ W) by adjusting the voltage with a subsequent recording of the output power.

As the rectifier power lowers relative to the optimal power $P_{rec} = 3.6$ kW, the output power decreases, while the efficiency increases to attain a peak value of 1.8 % for $P_{rec} = 1$ kW. When the rectifier power rises above the optimal one, the efficiency decreases. The latter is related, first, to the reduction of the output power due to the 'overheat' of the active medium and, second, to the nonlinear growth of power losses in the thyratron. The results of this experiment show that an efficiency increase for a power consumption below the optimal one is attained with retention of the high temperature of the discharge channel, i.e., the high copper vapour density. Either an improvement of the thermal insulation of the AE or an introduction of an additional 'indirect' heating are required to ensure the high temperature of the channel for a relatively low power. These conclusions were confirmed for an AE having an improved thermal insulation whose efficiency is 1.2 – 1.3 % in the optimal thermal regime ($P_{rec} = 2$ kW).

To obtain a more complete estimate of the laser efficiency, the efficiency was determined from the power P_{ae} introduced into the AE. To this end, calorimetric measurements were made of the power losses in the thyratron and magnetoelectric links. Under excitation employing the circuit of Fig. 3a, the maximum efficiency was ~ 1.1% ($P_{ae} = 1.8$ kW) in the optimal steady-state thermal regime ($T = 1550$°C) and about 1.2 % ($P_{ae} = 1.4$ kW) in the transition mode. Under excitation with the circuit of Fig. 3b, the respective figures were 1.8 % ($P_{ae} = 2.0$ kW) and 2.9 % ($P_{ae} = 0.7$ kW).

3.4. Output power and physical efficiency in the amplification mode

When the AE under investigation is used as a radiation power amplifier in the 'master oscillator – spatial filter – power amplifier' system, the output power and the physical efficiency (the efficiency with respect to the power introduced into an AE) increase, with the circuit of Fig. 3a, to 23 W and to 1.2 % compared to 20 W and 1.1 % in the lasing regime and, with the circuit of Fig. 3b, to 46.5 W and to 2.3 % compared to 37 W and 1.8 % in the lasing regime. Therefore, a two-fold compression of the excitation pulses, which resulted in a 2.5-fold rise in atomic copper density (through the rise of the operating temperature from 1550 to 1630 °C), led to a two-fold increase in the output power (46.5 W/23 W ≈ 2) and the efficiency (2.33 %/1.24 % ≈ 2) of the AE. The maximum physical efficiency equal to 3.5 % was reached in the transition mode upon excitation with the circuit of Fig. 3b.

3.5. Dependence of the output power on the neon buffer gas pressure for the LT-30Cu 'Kristall' AE

The dependence of the output power on the neon pressure for the LT-30Cu 'Kristall' AE (Fig. 5) was obtained for an optimal power consumption ($P_{rec} = 3.3$ kW, $f = 10.5$ kHz). Upon changing pressure from 100 to 760 Torr (the atmospheric one), the total power lowered from 33 to 21.5 W (by ~ 35%), the output in the green line from 17 to 8.5 (by ~ 50%) and in the yellow line from 16 to 13 W (by ~ 19%). Therefore, the lowering of the total output power is related primarily to the lowering of the output in the green laser line. As pressure was increased, the pump pulse characteristics were impaired (the voltage and current pulses became longer) and there occurred a discharge contraction. Evidently, to further improve the AE efficiency at high pressures, one should not only form shorter high-voltage pump pulses, but also provide relatively uniform distributions of the temperature and the discharge current density over the section of the discharge channel. The experimental results and the above conclusions show that it is possible to provide stable CVL operation at near-atmospheric pressures and an output power of the order of the tens of Watts. The use of a high operating buffer gas pressure is one of the main methods to lengthen the service life of a sealed-off AE.

To further increase the output laser power, investigations were made of AEs with a large volume of the active (working) medium: $V = 350$ and 900 cm^3.

3.6. Constructional features and main parameters of the LT-40Cu and LT-50Cu 'Kristall' AEs

Constructively, the LT-40Cu 'Kristall' AE with $V = 350$ cm^3 differs from the LT-30Cu 'Kristall' AE in that

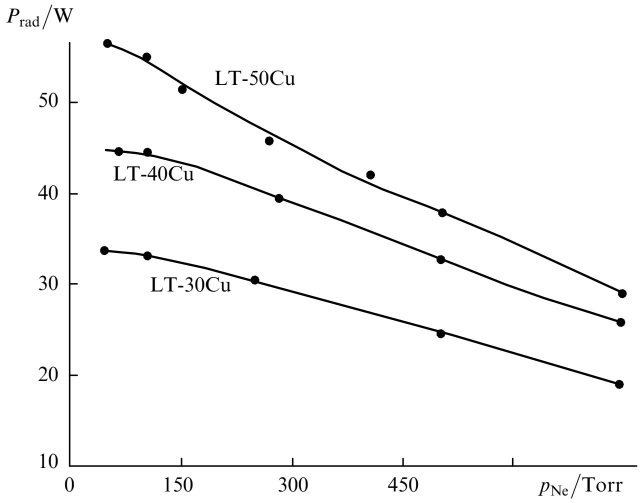

Figure 5. Dependences of the average total output power of the LT-30Cu, LT-40Cu, and LT-50Cu 'Kristall' AEs on the neon pressure for $f = 10.5$ kHz and a rectifier power consumption of 3.2, 4.0, and 5.5 kW, respectively.

its discharge channel is 30 cm longer (see Fig. 1). The LT-50Cu 'Kristall' AE with $V = 900$ cm^3 has the same overall dimensions as the LT-40Cu 'Kristall' AE but a 1.6 times larger diameter of the discharge channel (32 mm). The AEs were excited employing a power supply with a circuit shown in Fig. 3b. The average output power reached with a plane-spherical cavity laser (the radius of curvature of the totally reflecting mirror was 3.5 m) was, for a power efficiency relative to the rectifier of about 1 %, 40 – 44 W for the LT-40Cu 'Kristall' AE and 50 – 55 W for the LT-50Cu 'Kristall' AE. The output power in the amplification mode was 55 – 60 W and 65 – 70 W, respectively (Table 2).

3.7. Dependence of the output power on the neon buffer gas pressure for the LT-40Cu and LT-50Cu 'Kristall' AEs

Fig. 5 shows the total output power as a function of neon pressure for these AEs. When the pressure was varied from 50 to 760 Torr, the output power lowered by $\sim$ 35% for the LT-30Cu 'Kristall' AE, by $\sim$ 43% for LT-40Cu, and by $\sim$ 48% for LT-50Cu. The lowering of the total output power is primarily related to the reduction of the output power of the green line. A comparison of the curves suggests that the relative reduction in output power is greater for discharge channels of larger length and diameter, i.e., for larger volumes of the active medium. That is why higher-volume AEs have, as a rule, lower operating pressures. The operating pressure selected for an LT-30Cu 'Kristall' AE is 250 Torr, whereas it is 100 – 150 Torr in an LT-50Cu 'Kristall' AE (see Tables 1 and 2).

3.8. Dependence of the output power on the pulse repetition rate

The frequency characteristics of the AEs (Fig. 6) were recorded employing the excitation circuit of Fig. 3b. As the pulse repetition rate was increased from 10.5 to 20.5 kHz, the output power of an LT-40Cu 'Kristall' AE (curve *1* in Fig. 6) decreased by $\sim$ 14% with retention of an efficiency of about 1 % while the output power of an LT-50Cu 'Kristall' AE decreased by 13 %, also with retention of an efficiency of about 1 %. As the repetition rate was decreased, the output power sharply decreased due to an increase in power losses in the thyratron (because of the increase in the anode voltage), a reduction of the fraction of power that goes into the AE heating, and the corresponding lowering of the temperature of the discharge channel. As the repetition rate was lowered from 10.5 to 6 kHz, the output power of the LT-40Cu and LT-50Cu 'Kristall' AEs decreased by 24 % and the efficiency from 1 to 0.75 %. When the storage capacitor with a capacitance $C_s =$ 1000 pF + 1000 pF = 2000 pF and the peaking capacitor with $C_{peak} = 235$ pF were replaced respectively with 1500 pF + 1500 pF = 3000 pF and 300 pF, the output power and the efficiency obtained for the repetition rate $f = 8$ kHz (see points *4* and *5* in Fig. 6) were virtually the same as those obtained for $f = 10.5$ kHz.

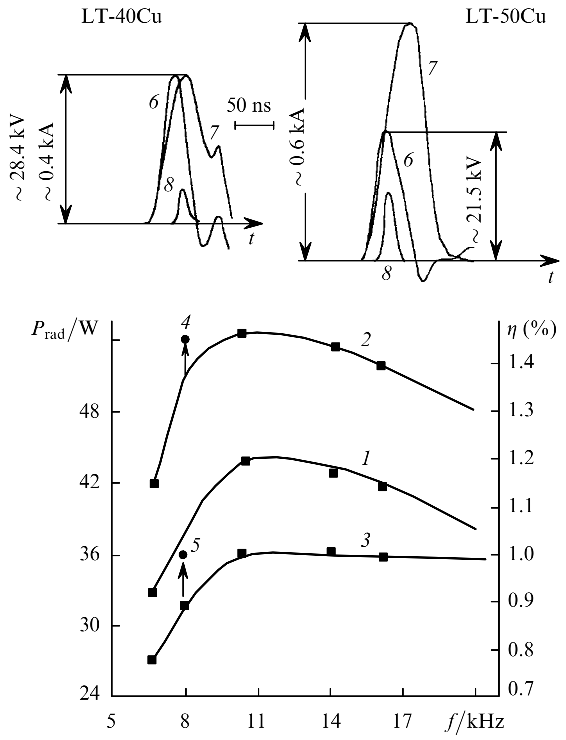

Figure 6. Dependences of the average total output power of the LT-40Cu (*1*) and LT-50Cu (*2*) 'Kristall' AEs and the efficiency η (relative to the power fed from the rectifier) (*3*) on the pulse repetition rate; oscilloscope traces of the voltage (*6*), discharge current (*7*), and output (*8*) pulses of the LT-40Cu and LT-50Cu 'Kristall' AEs for a pulse repetition rate $f = 10.5$ kHz; the points *4* and *5* were optimised for $C_s =$ 1500 + 1500 pF.

3.9. Results of the tests of an LT-40Cu 'Kristall' AE fed from an electronic tube power supply

We now analyse the results of tests of the LT-40Cu 'Kristall' AEs with an electronic tube power supply (the switch is a GMI-29A modulator tube developed by the 'Altek' Co. (Moscow). This power supply is capable of producing 40 – 70-ns pulses in a wide range of pulse repetition rates and is highly reliable in operation. Ten standard commercial AEs were picked out of different production lots without special sorting out. The samples were put to a test at the same repetition rate $f = 12$ kHz.

The spread in optimised power consumption and output power proved to be quite small: $\Delta P_{use} = 150$ W (3.6 %), $\Delta P_{rad} = 2$ W (4.2 %). We used a plane-spherical cavity with the radius of curvature of the totally reflecting mirror equal to 3.5 m. The output power obtained with an electronic tube power supply was 1.2 times higher than that obtained with a thyratron power supply (48 W/40 W = 1.2).

3.10. AE storage life

An important reliability parameter of an AE is the storage life. The guaranteed storage life of sealed-off commercial AEs is no less than five years. In 1982, two 'Kristall'-type AEs with a metal-ceramic shell were shelved in laboratory conditions to carry out a storage life test. No seal failure occurred over a 16 year storage period and the purity of gas was retained. The parameters of the AEs were totally reproduced in 1998. This is evidenced by the curves *1* and *2* in Fig. 7, which represent the dependence of the output power on the power supplied from the rectifier for a pulse repetition rate of 8 kHz. The excitation circuit was of the type diagrammed in Fig. 3a with capacitances of the storage and peaking capacitors of 2200 and 470 pF, respectively. Curve *1* was recorded in 1982 and curve *2* in 1998. It is likely that the difference in output power of 1 W for an optimal power consumption of 2.35 kW is associated with the scatter of the characteristics of the TGI1-2000/35-type thyratrons employed at different times. Curve *3* was recorded in 1998 using the excitation with the circuit of Fig. 3b and $f = 10.5$ kHz. The curve shows that doubling the pump pulse voltage and its two-fold compression result in a two-fold rise of the output power.

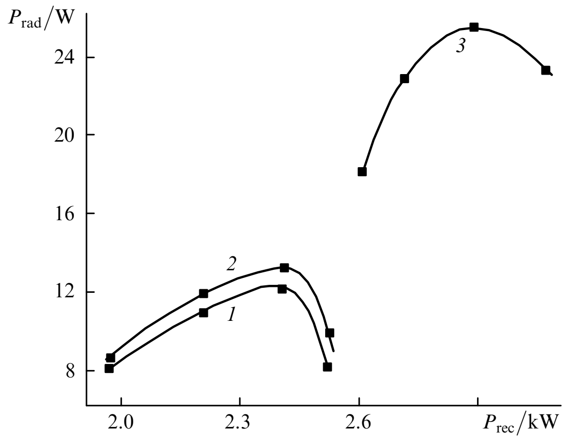

Figure 7. Average total output powers of a storable GL-201 copper vapour AE as functions of the power fed from the rectifier recorded in 1982 (*1*) and 1998 (*2, 3*).

4. Dependences of the specific AE characteristics on the volume of the active medium

The output power of commercial sealed-off AEs of the 'Kulon' and 'Kristall' series given in Table 1 is the result of optimisation of the electric parameters of the pump circuit for an operating neon pressure in the AEs. In the selection of the buffer gas pressure, both the output power and the service life of the AEs were taken into account. For all of the copper vapour AEs (with the exception of LT-50Cu 'Kristall'), the guaranteed service life (the minimal operating time) is no less than 1000 h. The guaranteed service life of the LT-50Cu 'Kristall' AE has thus far been 500 h, even though the store of the active material is large enough to provide a service life 3–4 longer. This limitation is due to the fact that the statistical data on the service life are insufficient.

A partial investigation was made of an LT-50Cu 'Kristall'-based sample AE with a discharge channel 30 cm longer (the electrode separation is ~ 150 cm, $V = 1200$ cm^3). The output power in the lasing regime with a plane-spherical cavity (the radius of curvature of the non-transmitting mirror was 3.5 m) was about 60 W and in the amplification mode about 80 W.

Based on the data of Tables 1 and 2, Figs 8 and 9 exhibit the output characteristics as functions of the volume of the AE medium. These dependences show the possible prospects and ways of improving the efficiency of the AEs with a large volume of the active medium. The curves representing the output power in the lasing (curve *1*) and amplification (curve *2*) modes are given in Fig. 8. As the active medium volume varies from $4-5$ cm^3 (LT-1Cu and LT-1.5Cu 'Kulon') to ~ 900 cm^3 (LT-50Cu 'Kristall'), the output power rose from ~ 1.5 to 55 W in the lasing regime and to 70 W in the amplification mode. While the volume increased by a factor of ~ 225 (900 cm^3/4 cm^3), the output power rose by only a factor of 47 (70 W/1.5 W), i.e., about 5 times less. Starting from the data on the output power in the amplification mode and the power inputted in the AEs, we plotted the dependences of specific power extraction P_{rad}/V and specific power consumption P_{use}/V on the volume of the active medium. While the specific power extraction in a 'Kulon' AE ($V \approx 4$ cm^3) amounts to ~ 0.5 W cm^{-3}, in an 'Kristall' AE ($V = 900$ cm^3) it is 0.08 W cm^{-3}, which is approximately 5 times lower. This is indication that an LT-50Cu 'Kristall'-type device (discharge channel 3.2 cm in diameter) is potentially capable of delivering an output power up to hundreds of Watts.

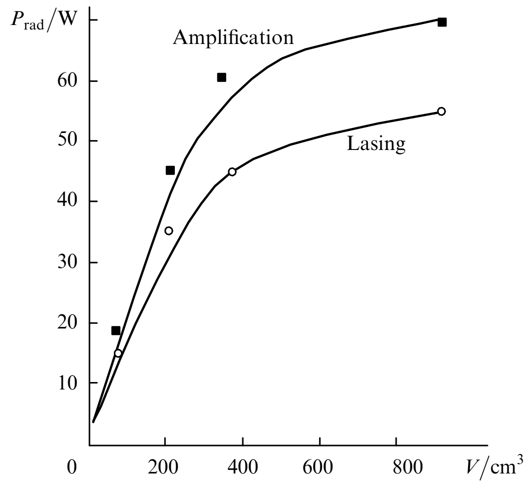

Figure 8. Average total output power of a copper vapour AE as a function of the active medium volume in the lasing and amplification modes.

To validate this possibility, the dependences of the temperature of the wall of the discharge channel, which harbours the active medium (copper), and the atomic copper density on the volume of the active medium were additionally plotted in Fig. 9. On the one hand, the P_{use} curve indicates that it is necessary to input a specific power up to 100 W cm^{-3} into the active medium of a small-volume AE.

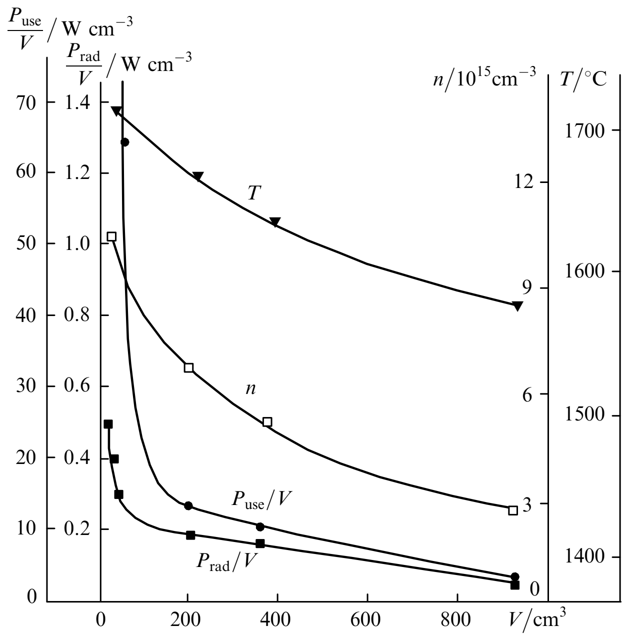

Figure 9. Dependences of the specific power extraction from an AE P_{rad}/V, its specific power consumption P_{use}/V, the temperature of the discharge channel T, and the atomic copper density n on the volume of the active medium.

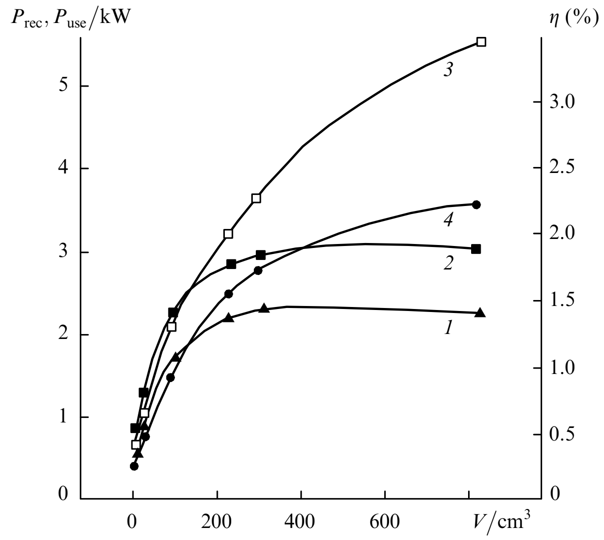

Figure 10. Efficiency relative to the power fed from the rectifier (*1*), efficiency relative to the power inputted in the AE (*2*), power fed from the rectifier (*3*), and the power P_{use} inputted in the AE (*4*) as functions of the volume of a CVL active medium.

But on the other, so high a specific (input) power is excessive for a larger-diameter AE, because there occurs, in our case even for a specific power above 4 W cm^{-3}, a lowering of the output power owing to the overheat of the active medium. In a 'Kulon' AE with $V = 4$ cm^3, the operating temperature of the discharge channel $T \sim 1700$ °C, which corresponds to an atomic copper density $n \sim 1.1 \times 10^{16}$ cm^{-3} [49]. In a 'Kristall' AE with $V = 900$ cm^3, the temperature $T = 1570$ °C and the density $n \sim 2.5 \times 10^{15}$ cm^{-3}, i.e., approximately five times lower (the T and n curves in Fig. 9).

The investigation conducted allows a conclusion that there exists a direct proportionality between the atomic copper density and the specific output power. Consequently, to accomplish a high-efficiency operation of a large-volume AE, the laser should be designed in such a way as to provide an operating temperature of the discharge channel up to 1700 °C without overheat of the active medium.

To summarise the performance evaluation of commercial sealed-off copper vapour AEs (see Tables 1 and 2), we plotted the dependences of the efficiency relative to the power fed from the rectifier (curve *1* in Fig. 10) and the efficiency relative to the power inputted in the AE (curve *2* in Fig. 10) on the volume of the active medium. The output powers in the AE amplification mode were taken to evaluate the efficiencies. This is of significance primarily for AEs of the 'Kristall' series, because they are mainly used in multimodule systems to form high-power beams. The output power in the amplification mode is approximately 1.3 – 1.4 times higher than that in the lasing regime. One can see from curves *1* and *2* that for 'Kristall' AEs the efficiency relative to the rectifier is $\sim 1.5\%$ and the efficiency relative to the power inputted in the AE is about 2 %.

5. Gold vapour AEs

The base models for gold vapour AEs ($\lambda = 0.628$ μm) are copper vapour AEs in which gold is put in place of copper as the active medium. In this case, the optimal temperature increases by 100 – 150 °C (up to 1800 °C). The LT-5Cu 'Kulon' AE is the base model for the LT-1Au 'Kulon' AE, the LT-10Cu 'Kulon' AE for LT-1.5Au 'Kulon,' and the LT-30Cu 'Kristall' AE for LT-4Au 'Kristall.' The output power of a gold vapour laser is approximately six times lower than that of a CVL for each of these models.

Fig. 11 gives the average total output power (curve *1*), the temperature of the discharge channel (curve *2*), the efficiency with respect to the power fed from the rectifier (curve *3*), and the efficiency relative to the power inputted in the AE (curve *4*) as functions of the power fed from the rectifier for an LT-4Au 'Kristall' AE. Use was made of the excitation circuit with a capacitive voltage doubling and a magnetic compression link (see Fig. 3b), the pulse repetition rate was 16 kHz, and the neon pressure was 250 Torr. The maximum output power was reached for a temperature of the discharge channel wall close to 1800 °C.

In this case, the efficiency relative to the power fed from the rectifier is $\sim 0.15\%$ and the efficiency relative to the power inputted in the AE was about 0.3 %. As the pressure was changed from 150 to 760 Torr, the output power lowered from 6.7 to 5.4 W (by $\sim 19\%$) and the efficiency relative to the power inputted in the AE from 0.32 to 0.25 %. With increasing pulse repetition rate, the reduction of the output power with pressure becomes more steep; for a repetition rate of 21.5 kHz, for instance, the output power lowered by as much as 41 %. When the repetition rate was raised from 10.5 to 21.5 kHz, the output power lowered from 6.3 to 4.6 W (by $\sim 27\%$). The neon pressure in the AE was 250 Torr and the maximum output power obtained after the optimisation of the excitation conditions at a neon pressure of 50 Torr was 8.5 W.

For an LT-1Au 'Kulon' AE, changing the neon pressure from 200 to 600 Torr resulted in a two-fold reduction of the output power (1.5 W/0.75 W = 2). The results obtained show that the operation efficiency of a gold vapour laser is high enough for near-atmospheric neon pressures, which provide an operating time of no less than 1000 h.

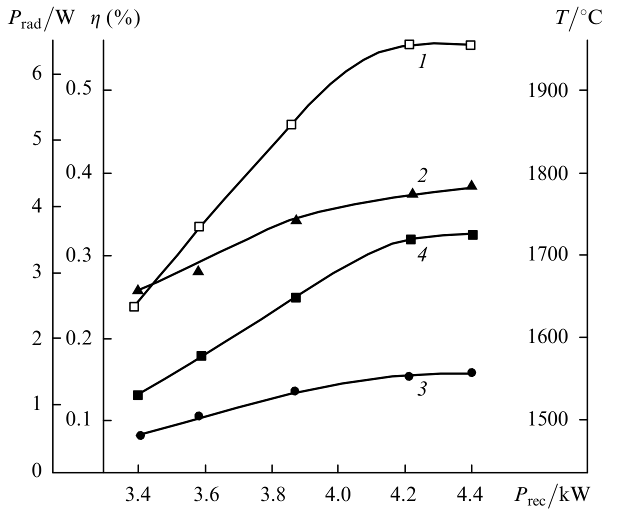

Figure 11. Average total output power (*1*), temperature of the discharge channel (*2*), efficiency with respect to the power fed from the rectifier (*3*), and efficiency relative to the power inputted in the AE (*4*) as functions of the power fed from the rectifier for an LT-4Au 'Kristall' AE.

6. Comparative analysis of the performance of domestic sealed-off lasers and their foreign analogues

To evaluate the performance of domestic commercial sealed-off CVLs of the 'Kulon' and 'Kristall' series, Table 4 shows the main parameters of foreign analogues with a similar output power.

Referring to Table 4, a domestic LT-30Cu 'Kristall' AE has the same output power as the Israel CVL-30 AE model [50]. Judging from the diameter of the discharge channel of a CVL-30 AE, the volume of its active medium would be expected to be ~ 2 times larger and the efficiency (the energy extraction per unit volume) to be lower by the same factor than the efficiency of the LT-30Cu 'Kristall' model. The efficiency of the English AGL-45 AE model [51] is ~ 4 times lower than that of the LT-40Cu 'Kristall' AE. The foreign analogues with an output power of over 10 W operate primarily in the mode of continuous circulation of the buffer gas, i.e., the lasers are supplied with additional operation-support elements. Moreover, a recharging of copper is performed after specific operating time intervals (300 and 400 h). Therefore, domestic instruments of the 'Kristall' series differ favourably from the foreign instruments with the same output power not only in efficiency, but also in

Table 4. Main parameters of the foreign analogues of CVLs.

Model	Country, company	Modification	d_{out}/mm	f/kHz	P_{rad}/W	$P_{510.6} : P_{578.2}$	Guaranteed minimal operating time/h Service AE life/h	P_{rec}/kW	P_n/kW
'Kristall' LT-30Cu	Russia, 'Istok' SSIE	sealed-off	20	11 ± 1	30 – 2	1:1	1000 ⩾ 2000	2.9 –	3.1 –
CVL-30	Israel, Nuclear Research Center	with a partial circulation	30	5.2	30 ± 5	> 1.2:1	400* –	– 5	– –
'Kristall' LT-40Cu	Russia, 'Istok' SSIE	sealed-off	20	11 ± 1	39 – 41	1:1	1000 ⩾ 2000	3.6 –	3.9 –
AGL-45	England, Oxford Lasers	with a circulation	42	6	45	< 1.7:1	> 300* –	– 6	– –
'Kulon' LT-5Cu	Russia, 'Istok' SSIE	sealed-off	14	12 – 18	5 – 9	< 1.5:1	1000 ⩾ 2000	1.2 –	1.5 –
SCuL05H	Bulgaria, Mashinoeksport	sealed-off	15	5 – 15	7	–	– 1000	– –	– –
CVL-5W	USA, Lasers Now	sealed-off	14	20	5	1.4:1	– ⩾ 800	– 1.2	– –
'Kulon' LT -10Cu	Russia, 'Istok' SSIE	sealed-off	14	14 – 17	10 – 15	< 1.5:1	1000 ⩾ 2000	1.5 –	1.8 –
CU10-A	England, Oxford Lasers	with a circulation	25	8 – 14	10	2:1	> 300* –	– –	– –
SCuL10H	Bulgaria, Mashinoeksport	sealed-off	25	5 – 15	10 – 12	–	– 500	– –	– –
CVL-10W	USA, Lasers Now	–	20	20	10	–	– > 500	– –	– –
CVL-10	Israel, Nuclear Research Center	sealed-off	20	–	10	–	– 1000	– –	– –

*Operating time with a single charging of copper.
Notes: d_{out} is the output beam diameter and P_n is the power consumption from the mains.

that they are sealed-off. The latter circumstance improves the reliability of a laser as a whole and makes its design simpler.

The instruments of the 'Kulon' series are also superior to foreign analogues. For instance, the efficiency of LT-10Cu 'Kulon' AEs is $\sim$ 2 times that of the CVL-10W (USA) [52] and CVL-10 (Israel) [50] models and $\sim$ 3 times that of the CU10-A (England) (see Ref. [8], p. 459 – 462) and SCuL10H (Bulgaria) [53] models. A CU10-A laser of Oxford Lasers operates with a circulation of neon. The operating time of its AE per single charging of copper is $\sim$ 300 h. The SCuL05H and SCuL10H lasers produced by Mashinoeksport are either of gas-flow or sealed-off design. For sealed-off AEs of the foreign lasers with an output power of 5 – 10 W, referring to Table 4, given as the principal reliability criterion is the service life (500 – 1000 h), which does not exceed the minimal (guaranteed) service life of the AE elaborated at the 'Istok' SSIE.

The highest-power Russian commercial AE is LT-50Cu 'Kristall.' In foreign countries (USA, France, Japan, etc.), gas-flow AEs with an output power of 100 – 750 W were elaborated in the implementation of the AVLIS (laser isotope separation) programme. A single AE operated in the amplification mode made it possible to obtain an output power of more than 750 W in the Lawrence Livermore National Laboratory (USA) in 1991, 400 W (1996) in the French CILAS company, and 615 W (1995) in the Japanese Toshiba company [8, 9].

Figure 12. LGI-202 'Kurs' copper vapour laser.

7. Radiation sources, lasers, and laser facilities

The investigations of CVL characteristics performed in Refs [38 – 44, 54 – 59] underlay the development and the production by the 'Istok' SSIE of highly efficient and reliable radiation sources of the ILGI-201 'Kareliya,' ILGI-202 'Klen,' and 'Kulon' types; the LGI-202 'Kurs' (1990) laser facility [60, 61] (Fig. 12); the 'Yantar', 'Yakhroma,' and 'Kulon' medical facilities [62 – 68]; and the 'Karavella' automated laser production facility [69 – 71] whose optical layout is diagrammed in Fig. 13. 'Karavella' is intended for precision material processing (a selection of samples are given in Fig. 14) and in specific cases is preferable [72] to similar solid-state laser facilities [71].

Recently, a new generation of low-bulk CVL facilities have been developed and promoted for various purposes.

8. Two-amplifier oscillator–amplifier system

We have investigated a laser with a modernised ILGI-201 'Kareliya' lasing emitter in which two LT-50Cu 'Kristall' AE were employed as power amplifiers to raise the output power. The master oscillator was a 'Kulon' AE with an output power of 3 – 4 W (with a diameter of the discharge channel $d = 12$ mm). The master oscillator with a telescopic resonator and a spatial filter–collimator was placed in a space-saving manner between the power amplifiers. The output power of the laser system was 105 W for $f = 10$ kHz and a divergence of 0.3 mrad, the peak power was $\sim$ 500 kW, and the pulse energy about 10 mJ. The temporal matching was not reached in this system: the output pulse duration of the master oscillator with a 'Kulon' AE was $\tau = 15 - 20$ ns and the pulse duration of the LT-50Cu 'Kristall' AEs was 30 – 35 ns. When an LT-30Cu 'Kristall'

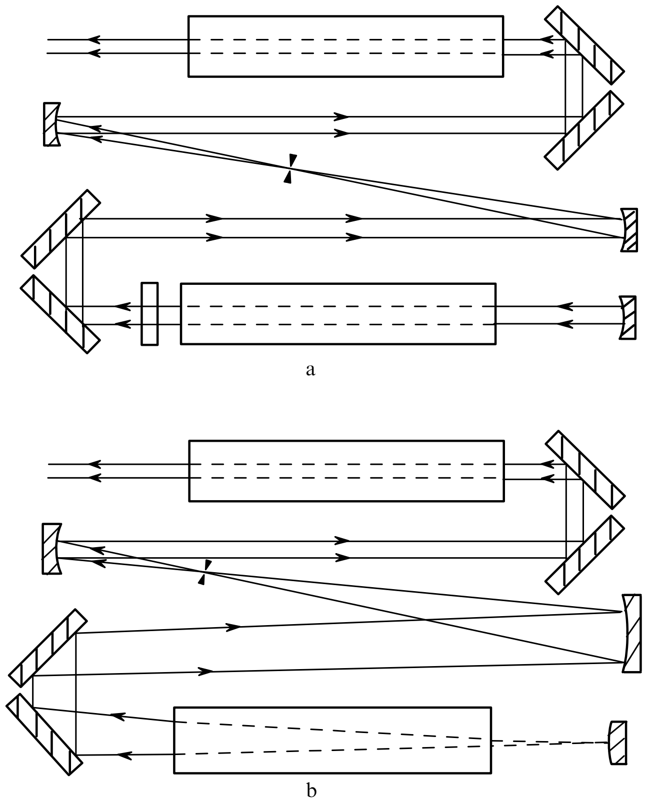

Figure 13. Optical layout of the 'Kareliya' CVL with a telescopic resonator (a) and a single mirror (b).

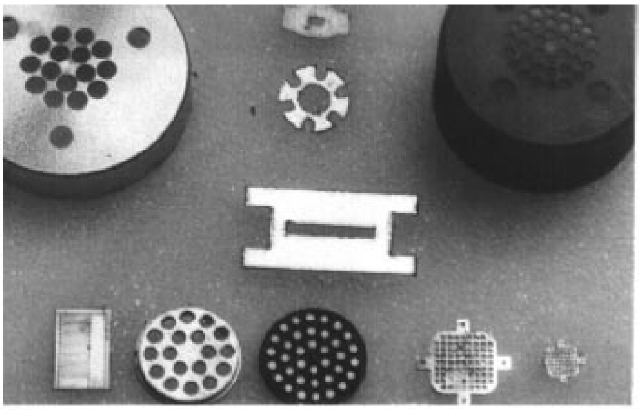

Figure 14. Sample workpieces fabricated with an automated 'Karavella' laser production facility.

AE with ≈ 30 ns was used as the oscillator, the energy extraction from a single LT-50Cu 'Kristall' AE was 70 W.

9. Conclusions

Long-term complex physical investigations have brought into existence for the first time a class of compact high-efficiency laser AEs with several record-breaking characteristics. The investigations conducted have shown that the 'Kulon' and 'Kristall' commercial sealed-off AEs with an output power of 1 – 15 W and 30 – 50 W in the lasing regime have a practical efficiency of 0.2 – 0.8 % and 1.0 – 1.2 %, respectively. The physical efficiency of the 'Kristall' AE is 1.5 – 1.8 % in the lasing regime and 2.3 – 3 % in the amplification mode. As the diameter and the length of the discharge channel, i.e., the volume of the active medium, increase, the efficiency of the AE increases while the specific power extraction, the specific power input, and also the temperature of the discharge channel lower.

An increase of the active volume from 4.2 cm^3 (LT-1Cu 'Kulon') to 900 cm^3 (LT-50Cu 'Kristall') results in a reduction of the operating temperature of the discharge channel from 1700 to 1570 °C, which corresponds to a reduction of the atomic copper density and the specific energy extraction by factors of 4 – 5. To improve the efficiency of a large-volume AE, its design, the composition of the gas medium, and the excitation conditions should be optimised for the operation at a copper vapour density close to 10^{16} cm^{-3} ($T > 1600$°C).

The sealed-off AEs of the 'Kulon' and 'Kristall' series excel their close foreign analogues in efficiency, guaranteed service life, and service conditions. Compared to the foreign analogues, the efficiency and the power extraction per unit volume of the 'Kulon' and 'Kristall' AEs is 2 – 4 times higher, the minimal operating time is nearly three times longer, while the sealed-off AE design obviates the need for additional operation-support elements.

The newly elaborated 'Klen' and 'Kareliya' radiation sources, 'Kurs' lasers, two-channel lasers, as well as 'Yantar' and 'Yakhroma' medical facilities produced on their basis, and a 'Karavella' production facility provide a basis for the development of a new generation of efficient lasers and laser facilities.

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