High-power excimer laser system

V.F. Losev, B.M. Kovalchuk, V.F. Tarasenko, Yu.N. Panchenko, N.G. Ivanov, I.N. Konovalov, E.N. Abdullin, A.N. Panchenko, V.B. Zorin, V.S. Skakun, V.P. Gubanov, A.S. Stepchenko, and V.S. Tolkachev

Institute of High-Current Electronics, Siberian Branch of the Russian Academy of Sciences, Tomsk

Received December 6, 2005

We report on the development of an excimer laser system with an output aperture of 40 cm. The system consists of five lasers, three of which are excited by an electric discharge and two others by an electron beam. The first laser generates a 200 to 250-ns duration pulse of radiation at λ = 308 nm, with the spectral line width of 0.9 cm^{-1}, and nearly diffraction limited beam divergence. This pulse is amplified in the active medium of other lasers. As a result, the pulse of radiation at the output of the third amplifier has energy of 5 J at the line width of 0.9 cm^{-1} and 37-μrad beam divergence. The energy of radiation at the output of the entire system is up to 330 J per pulse of 200 to 250-ns duration.

Introduction

Laser systems on halides of noble gases are the most powerful and efficient sources of coherent UV radiation. Today these are unique instruments for solution of many problems in basic and applied research, such as inertial thermonuclear fusion, physics of interaction of a super high intensity radiation with matter, generation of X-ray radiation, acceleration of particles in super strong electromagnetic fields, etc. Nowadays the most powerful excimer laser system has been built in the USA, the Nike system,[1] which delivers pulses of 5 kJ energy at the pulse duration of 240 ns (full width at half maximum) at the wavelength λ = 248 nm (KrF molecules). The output amplifier in this system has an aperture of 60×60 cm. The system has been built for solving the problem of inertial thermonuclear fusion where it is now being used. It also helps experimenting on formation of high-power pulses of nanosecond duration and studying their interaction with a target.

The second in the world rank excimer laser system has been built in Japan,[2] it is called SuperAshura. The output amplifier of this system has an aperture of 61 cm. It can lase about 3.7 kJ per pulse of ~240-ns duration at λ = 248 nm. This laser system is used in the experiments with generation of high-power nano- and picosecond-duration radiation pulses and in radiation and matter interaction. In the United Kingdom, they have created Titania high-power laser system, on a KrF molecule, with the output energy ~1 kJ per pulse of ~150-ns duration.[3] The aperture of the output amplifier was 42 cm. This system is exploited in the experiments on generation and interaction with matter of high-power laser beams of the picosecond and femtosecond duration.

In Russia, high-power excimer lasers and laser systems are also being constructed (see Refs. 4–12). For example, at the Institute of High-Current Electronics, we have developed the laser system MELS-4k, with the aperture of the output amplifier of 25×25 cm, the lasing energy at the wavelength of 308 nm reaches 200 J at the pulse duration of 250 ns (see Refs. 6 and 7). There are lasers with apertures of 40 and 60 cm (Refs. 9–11), which, being XeCl-molecule-based systems, generate pulses with energy of 660 J and 1.9 kJ, being ~350 and 250 ns duration, respectively. At the P.N. Lebedev Physics Institute RAS (Moscow), a laser system has been put into operation[12] with the Garpun output module, which has the output aperture of 16×18 cm and generates an 80-J pulse of 100-ns duration in KrF.

In this paper, we report on completion of the development of a five-stage laser system with an output aperture of 40 cm, which, on a XeCl molecule, delivers up to 330 J per pulse of a high quality radiation of ~250 ns duration. We discuss experimental results obtained with this system.

Instrumentation and experimental results

Our laser system consists of five excimer lasers ("Foton-1, -2, -3, -4, -5"), a synchronization and triggering system, and optical coupling elements. In the Foton-1, -2, -3 lasers the working mixture is excited with an electric discharge, while in Foton-4 and Foton-5 it is excited with an electron beam. All the experimental measurements of lasing parameters were conducted by conventional methods using standard instrumentation. To measure temporal and energy characteristics of laser pulses, we used a FEK-22 SPU vacuum photodiode, TPI and IKT-2N calorimeters, and OPHIR with an L30A-EX gage head. The signals of interest were recorded with TDS oscillographs.

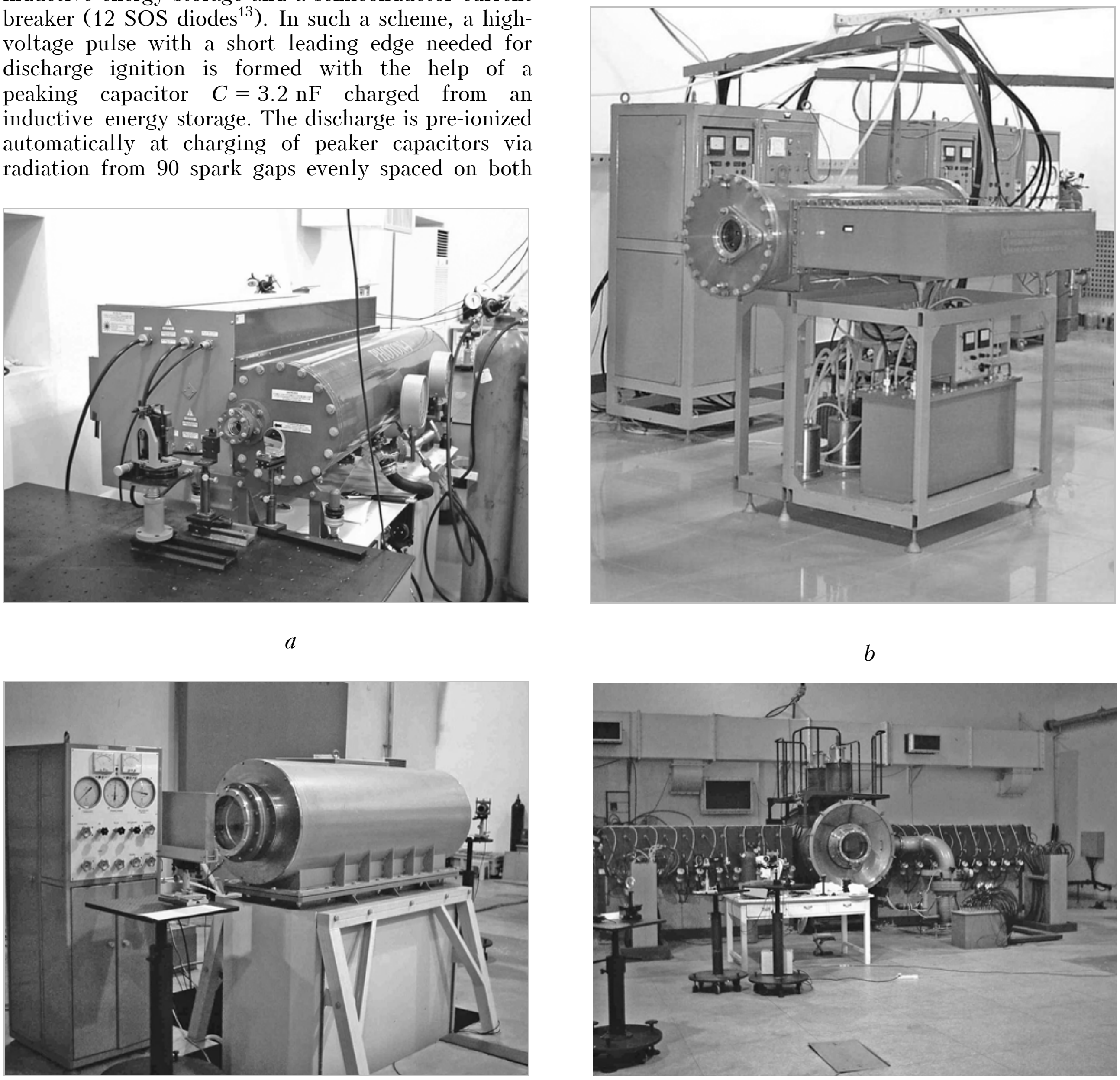
0235-6880/06/02–03 173-06 $02.00

Electric-discharge lasers

The first laser, Foton-1, is shown in Fig. 1*a*. It has a steel laser chamber of 35-cm diameter with the electrodes of discharge gap. The length of the electrodes is 107 cm (at the active length equal to 102 cm). The interelectrode gap is 4 cm wide. A rectangular window tailored to fit the length of laser chamber is hidden under an insulator through which the discharge is supplied with power. The insulator surface carries the elements of the laser excitation system, whose high-voltage parts are covered with a metal sheath.

For excitation, an electric circuit is used with inductive energy storage and a semiconductor current breaker (12 SOS diodes[13]). In such a scheme, a high-voltage pulse with a short leading edge needed for discharge ignition is formed with the help of a peaking capacitor $C = 3.2$ nF charged from an inductive energy storage. The discharge is pre-ionized automatically at charging of peaker capacitors via radiation from 90 spark gaps evenly spaced on both sides near the anode. The energy bulk for the active medium comes from a 550 nF accumulator charged to 18 kV. The cavity consists of mirrors with a dielectric coating, whose reflection coefficients are 100 and 20%. In the mixture Ne : Xe : HCl = = 1520 : 10 : 1 used at a pressure of 2 atm the peak laser generation energy exceeded 1.5 J at a pulse duration of 300 ns and the overall efficiency of 1.35%.

Two other electric-discharge lasers, Foton-2 and Foton-3 (see Refs. 14 and 15), have almost the same pumping circuits and the design. The appearance of one of them is shown in Fig. 1*b*.



a *b* *c* *d*

Fig. 1. External appearance of the lasers Foton-1 (*a*), Foton-3 (*b*), Foton-4 (*c*), and Foton-5 (*d*).

The lasers consist of three main units: a gas-discharge chamber with a pump generator and an electric and pneumatic control boards. The chamber houses a vacuum diode, the source of soft X-rays, the electrodes forming the discharge gap, and an insulator of a high-voltage input. The active electrodes are made from stainless steel. The spacing between electrodes for Foton-2 and Foton-3 are 5.4 and 9 cm, and the lengths are 80 and 100 cm, respectively. To direct the X-radiation to the discharge gap, there is a window on the cathode side covered with an 80-μm thick titanium foil. The anode of the discharge gap is connected to the pump generator placed outside the chamber through the insulator by metal stud bolts. Our arrangement of the generator-to-anode connection and reverse current leads allows us to minimize inductance of the discharge contour.

A vacuum diode of the X-ray source is packaged inside a metal cylinder, which holds the anode and a cold cathode operating in the mode of explosive electron emission. The cathode consists of strips of foil-clad fiberglass plastic. The strips are fixed on a spacing grid, which is covered with a 40-μm thick titanium foil in order to capsulate a vacuum diode. It also outputs X-rays from the diode. Tantalum foil was used as an anode. A vacuum diode was evacuated with an oil-vapor vacuum pump down to residual pressure of 10^{-4} mm Hg.

Power supply of the vacuum diode is a three-stage Arkadiev–Marx generator with a shock capacitance of 15 nF. The generator was connected to a vacuum diode via a high-voltage cable KVI-120. Positive polarity voltage pulse of 50–55 kV amplitude and 700-ns duration was applied to the anode. The X-ray dose at the cathode was ~20–30 mR.

The main elements of the laser pump generator are the storage capacitor, commutator, and peaking capacitor. The storage capacitor C_L consists of two (Foton-2) or three (Foton-3) connected in parallel lines of FL-300 type. The electrical length of the line is 300 ns, its capacity is 150 nF, and the impedance of 1 Ω. A pulse charging of the lines is performed from the capacitor C_s of IK-100 type, which connects the lines through the KVI-120 cable. The capacitor C_s can be charged up to 40–65 kV voltage. The peaking capacitors C_2 = 4.9 nF (Foton-2) and 6.9 nF (Foton-3) determining formation of a volume discharge in a discharge gap are ceramic KVI-3 capacitors (20 kV, 680 pF).

For a low-inductance commutator we use a multichannel track-type spark gap. The anode is made from a 1-mm thick steel plate and the cathode is made of a rod 15 mm in diameter. The length of the electrodes is 80 cm (100 cm), a gap between the electrodes is 4 mm (6 mm). Near the cathode, along its entire length, there is an ignition electrode made in the form of foil tabs. The spark gap is initiated with a high-voltage pulse applied to the cathode via spark gaps. The bodies of the dischargers are made from dielectric tubes with the outer diameter of 65 mm. In the active mode, dischargers are filled with dry air at a pressure of 4 to 6.6 atm.

High-voltage pulse that initiates all the spark gaps is produced by a high-voltage thyratron of TGI1-1000/25 type. The radiotechnical delay lines in the system ensure an orderly start of the pump generator and the source of X-rays.

The plane-parallel plates of fused silica served windows of the laser chamber. In a generation mode, laser cavity was formed by an external non-conducting mirror with a 97% reflection at the wavelength of 308 nm and a laser chamber window. Laser mixture consisted of Ne/Xe/HCl at an overall pressure of 3.5–4 atm.

In a free generation mode, the Foton-2 and Foton-3 lasers generate the pulses of 250 to 300 ns duration and 3.5 and 10 J energy per pulse, respectively.

Electron-beam-pumped lasers

Figure 1*c* shows the appearance of a Foton-4 laser. The laser consists of the Arkadiev–Marx generator (a high-voltage pulse generator, HVPG), a vacuum diode, a laser chamber, a system of gas refilling, and an electric control panel. Current is supplied to the vacuum diode directly from the generator assembled inside the diode housing.

Thus, for the HVPG we used vacuum insulation of its high-voltage parts. This construction allows us to minimize the inductance of a vacuum diode supply line, as well as the size and weight of the accelerator. The HVPG has three parallel arms that enable the decrease of its inductance and weaken the erosion of the discharger electrodes. The space with the spark dischargers in each arm is filled with the mixture of dry air and SF_6. The capacity of each stage of an arm is 0.18 nF. The accelerator is started through a controlled discharger, which grounds a high-voltage cable supplying HVPG with the high voltage. The discharger itself is initiated by a high-voltage pulse from a thyratron-based generator. The cathodes of a vacuum diode having 110 cm total length are placed on a mount fixed directly to the upper stage of the HVPG.

The laser chamber, of 25-cm inner diameter, is mounted between the cathodes in the center of a vacuum diode and works as anode. The chamber along its entire length is fixed with a metal plate to the diode housing. The plate makes current spread better and reduces the electron beam losses caused by the influence of its own magnetic field. Without such a plate and with the current closure only through the ends of the gas chamber, the losses can reach 50%. The electron emitters of the cathodes of the vacuum diode made from velvet. The anode–cathode gap is 7 cm wide. As a result, there are four radially converging electron beams injected into the laser chamber through eight windows, the latter being arranged by two in a row with the total length of 120 cm. Each window is vacuum-tightened with titanium foil laid over a metal grid. A residual gas pressure inside the body of the HVPG and a vacuum diode is $5 \cdot 10^{-5}$ mm Hg.

At a charging voltage of 85 kV, the generator forms a 1000 ns voltage pulse with an amplitude of 480 kV and total current up to 74 kA in the vacuum diode. The electron beam formed in the diode provides a uniform excitation of the laser gas mixture.

The windows of our laser chamber are plane-parallel plates from fused silica of 300 mm diameter. In a generator mode, the laser cavity was formed by the outer mirror with an aluminum coating and by the window of the laser chamber. The laser gas mixture comprised argon, xenon, and HCl. With Ar : Xe : HCl = 1000 : 10 : 1 under a pressure of 2 atm and at a charging voltage of 85 kV, the pulse energy reached 120 J. Pulse duration (FWHM) was about 250 ns.

The appearance of a Foton-5 laser is shown in Fig. 1*d*.

Laser gas mixture is excited by a radially converging electron beams from 6 sides.[8] The beam is formed in the vacuum diode containing 18 cathodes. The cathode profile was chosen according to numerical calculations of the beam parameters using a unique two-dimensional code. The emitting surface of the cathodes was made of carbotextime (a graphite-fibrous material with a specific resistance of $\sim(5–50) \cdot 10^{-2}\ \Omega \cdot \text{m}$) and then was covered with velvet. The width of the emitting surface is 120 mm; the total area of the cathode emitting surface is 0.95 m^2. The interelectrode gap between the emitting surface and the supporting structure of the output window is 6 cm. The supporting structure has 18 windows (three in a row with the total length of 150 cm). The geometrical transparency of the beam output system is ~75%. Beam entrance to the laser chamber was realized with a 40-μm thick titanium foil. The diameter of the laser cavity is 41 cm, and the volume about 200 liters.

The voltage pulse applied to the diode is formed using two parallel linear transformers with a vacuum insulation of the secondary coil. The transformers consist of 10 stages, each composed of 8 IK-100-0.17 capacitors (100 kV, 0.17 μF, 50 nH), the output power of a stage is ~12 GW. The diode collector is supplied with voltage through vacuum lines serving also secondary coils of the transformers. The diameter of the diode vacuum cell is 131 cm, and its length is 120 cm. Cathode collector is a cylinder of 114 cm in diameter and 120 cm in length. The collector is pending coaxially with the vacuum chamber with two springs on top of the vacuum chamber. The vacuum system is evacuated by two AVDM-250 pumps with nitrogen traps down to a residual pressure of $(3–4) \cdot 10^{-5}$ mm Hg.

At a charging voltage of 85 kV, the voltage pulse in the vacuum diode reaches 550 kV, the net current reaches 320 kA (this is the sum of two currents shown in Fig. 2), and the energy running from transformer to the diode raises to 87 kJ. At the charging voltage of 80 kV, the voltage in the vacuum diode is about 440 kV, the net current is 290 kA, and the energy transmitted to the diode is 78 kJ. The energy pumped into the gas increases with the increase of pressure up to 2.5 atm, and then, as the pressure is further raised to 3.5 atm, it keeps almost stable. The maximum energy pumped into the gas by the electron beam was ~19 kJ. The efficiency of energy transmission from the primary storage to the gas is ~19%, which is close to the value obtained with traditional water line accelerators.[1–3]

The windows of the laser chamber were plane-parallel plates of 400-mm diameter. This laser was tested, in a generator operation, with a resonator formed by a plane mirror with an aluminum coating and the laser chamber window. The working mixture of argon, xenon, and HCl was prepared right in the laser chamber. With Ar : Xe : HCl = 760 : 20 : 1 mixture at a pressure of 2 atm and a charging voltage of 85 kV pulse energy reached 660 J (see Ref. 8). Pulse duration (FWHM) was ~350 ns. Non-uniformity of the density distribution of the laser beam energy did not exceed 10%.

Laser system

To synchronize operation of all the setups we used the so-called clock and startup system. Its functional diagram is depicted in Fig. 2.

The entire laser system is controlled using a PC, which forms instructions for a synchro generator. The latter controls pulses, so that their amplitude is 600 V, and regulates the interpulse periods. These pulses initiate four thyratron generators and a Foton-5 magnetic bias generator. The latter generates two magnetic bias pulses, which are directed to the linear transformers and magnetize their cores in a specified direction prior to its operation. Thyratron generators produce negative pulses with the amplitude of ~20 kV. These pulses initiate spark dischargers Foton-1, -2, -3 and are also applied to inputs of generators 4 and 5. Both generators produce negative pulses with the amplitude of ~85 kV initiating the track-type dischargers Foton-2, -3, and Foton-4, and the trigger generators G-1 and G-2. The trigger generators form forty negative pulses with the amplitude of 85 kV, which initiate the transformer discharge stages of Foton-5. A computer control helps to synchronously switch on and off the charging capacitive storages of all lasers, which allows one to achieve their simultaneous charging.

Thus, the first stage of laser system's operation involves charging of the storage capacitors, whose switching-on moments depend on the time needed to charge each of the Fotons. Then, a pulse to start the magnetic bias generator of Foton-5 is applied followed by the pulses to switch on the thyratron generators Foton-1, -2, -3, and -4 in a specified order having thus started the entire system.

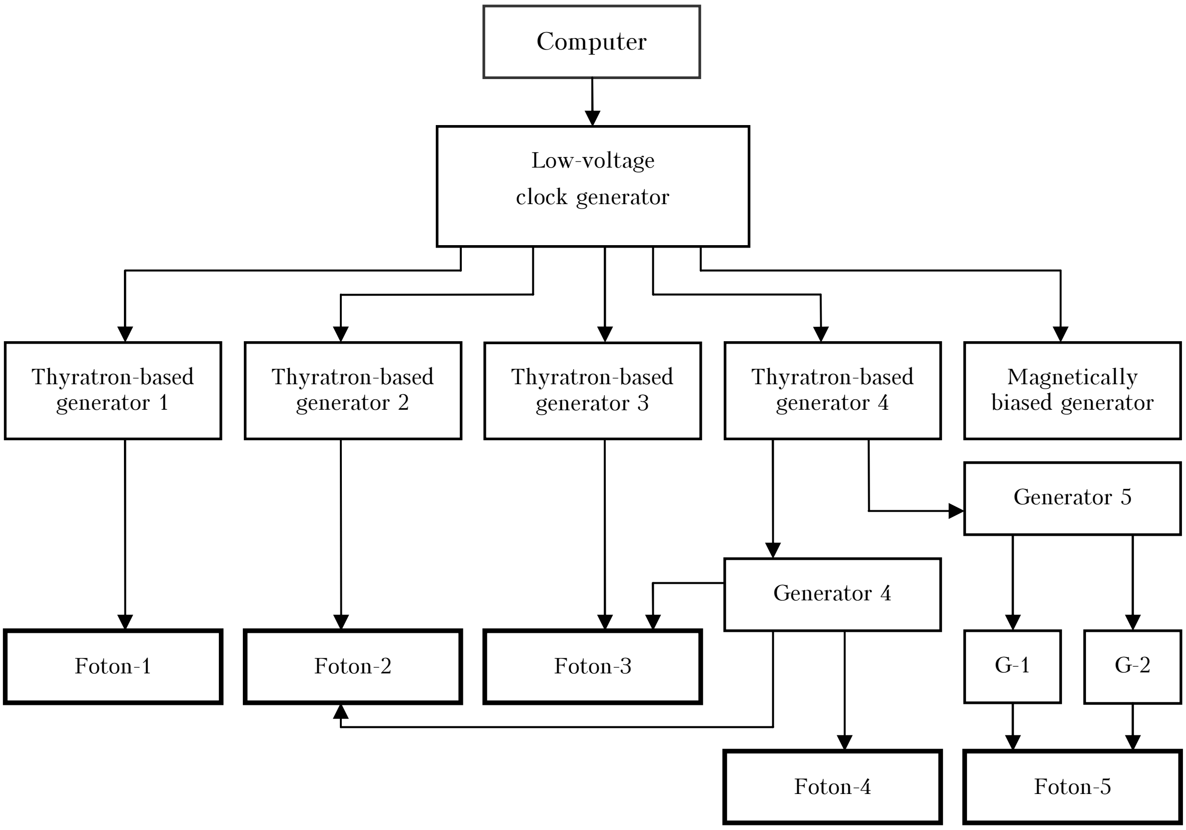


Fig. 2. Block-diagram of the clock and startup system.

All the lasers of the system are used in the amplifying mode with all the windows of the laser chamber mounted at the angle excluding any optical feedback. Based on the Foton-1, we constructed the main generator (see Ref. 13). Its optical arrangement allows us to form a high-quality beam in some region of the active volume, which is used as a master oscillator with its subsequent amplification in the other part of the volume. To obtain the minimum divergence, we used two diaphragms in the cavity, each being 2 mm in diameter. In this case, for a 1.5 m cavity, the Fresnel number was ~2. For the spectral selection, we used a diffraction grating with 1800 grooves/mm and operating in the autocollimation mode. A feedback in the resonator was performed through the first order of diffraction. To reduce noise in the output signal, the beam was exited through a semitransparent mirror with a reflection coefficient $R = 30\%$. Then a low-power quality radiation of the main generator was amplified during two round trips through the same active medium gradually widening to 7 mm output diameter. As a result, Foton-1 gave a pulse of 50 mJ, 250 ns duration, and spectral line width of 0.9 cm^{-1}. Divergence of an 80% power beam was within 0.13 mrad angle, which 1.2 times exceeded the diffraction limited one.

This beam was widened by a lens telescope with a magnification factor $M = 1.5$ to match the beam diameter with the sizes of the active media of Foton-2 and Foton-3 units. In the active medium of Foton-2 chamber, the beam was intensified during three-pass travel, and in the active medium of Foton-3 during a single pass. The output beam diameter was 3 and 6 cm, respectively. To match beam diameter with the size of the active media of Foton-4 and Foton-5, we used a lens telescope with the magnification factor 5. Upon widening by the telescope, the beam was amplified during a single pass in the active medium of Foton-4 and during a single or two-pass travel in the active medium of Foton-5 chamber.

Experimental results obtained with the laser system are summarized in the Table.

Table. Emission characteristics of Foton lasers

Laser	Operating mode	Energy, J	Pulse duration, ns	Line width, cm^{-1}	Divergence, μrad
Foton-1	Generator	1.5	300	–	–
	Main Generator	0.05	200–250	0.9	130
Foton-2	Generator	3.5	250	–	–
	Amplifier	0.5	200–250	0.9	60
Foton-3	Generator	10	300	–	–
	Amplifier	5	200–250	0.9	37
Foton-4	Generator	120	250	–	–
	Amplifier	40	200–250	–	–
Foton-5	Generator	660	350	–	–
	Amplifier	250, 330	200–250	–	–

From the Table we can see that the highest value for the lasing energy is 330 J. This energy level was obtained with a single pass amplification in Foton-5, when the active medium had the smallest fluxes of the amplified spontaneous emission (ASE) and the lowest energy losses due to absorption by the active medium. Under double-pass amplification, both the absorption and competition from the ASE, whose intensity grew because of its reflection from the back mirror ($R = 99\%$). This reduced the amplified radiation energy down to 250 J.

The spectral and spatial radiation parameters were recorded only for the first three setups. Divergence was determined by the size of the spot in the focal plane of the lens with a focal length $F = 13.5$ m, and the line width was measured with the Fabry–Perot interferometer. In both cases, the intensity distribution was recorded with a CCD camera. Measurements of the line width showed that after amplification it remains unchanged and equals 0.9 cm^{-1}. Generally, divergence of the amplified radiation became smaller as the beam diameter increased. However its ratio to the diffraction limit exhibited a slight increase. Perhaps, this was due to distortions in the active medium and in the optical path.

The output energy levels of the main amplifier are shown Fig. 3 as a function of the input energy. The input energy varied via switching off one of the amplifiers of Foton-3 or Foton-4. We can see that saturation of the amplification in Foton-5 is reached only at a full operation of all the amplifiers with the amplification coefficient of 10. A laser beam spot recorded on a piece of photo-paper had a sufficiently uniform distribution with the diffraction fringes due to inhomogeneities of the optical path. This proves high spatial coherence of the output radiation.

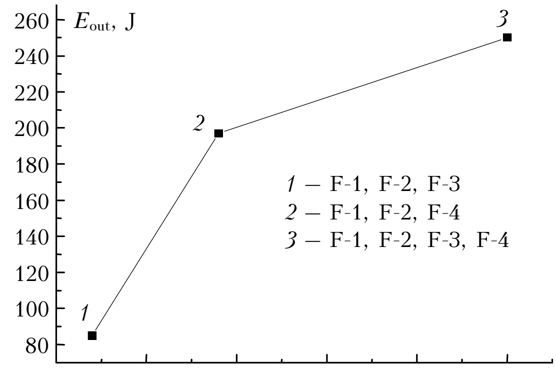


Fig. 3. The output energy of Foton-5 under a double-pass amplification versus the strength of the input signal.

Conclusion

Thus, we have built an excimer laser system with the output aperture of 40 cm and radiation energy up to 330 J per pulse. The system allows us to form laser pulses with 0.9 cm^{-1} spectral width and small divergence. The duration of the output pulse is 200 to 250 ns. Each system's stage can function as an independent generator yielding the pulses of 1.5 to 660 J in energy and 200–350 ns duration.

With this system, we are planning to experimentally investigate formation of laser pulses with different parameters and radiation–matter interactions.

Acknowledgments

This study has been carried out under a contract with the Chinese Northwest Nuclear Technology Research Institute.

We thank our colleagues from the Institute of High-Current Electronics SB RAS who have contributed to this research work.

The work was supported in part by the Russian Foundation for Basic Research (No. 05-08-50321a).

References

1. S.P. Obenschain, S.E. Bodner, D. Colombant, K. Gerber, R.H. Lehmberg, E.A. McLean, A.N. Mostovich, M.S. Protko, C.J. Powley, A.J. Schmitt, J.D. Sethian, V. Serlin, J.A. Stemper, C.A. Sullivan, J.P. Dahlburg, J.H. Gardner, Y. Chan, A.V. Deniz, and T. Lehecka, Phys. Plasma **3**, No. 5, 2098–2107 (1996).
2. Y. Owadano, I. Okuda, I. Matsumoto, I. Matsushima, E. Takahashi, E. Miura, H. Yashiro, T. Tomie, K. Kuwahara, and M. Shinbo, Fusion Eng. and Design **44**, 91–96 (1999).
3. E.J. Dival, C.B. Edwards, G.J. Hirst, C.J. Hooker, A.K. Kidd, J.M.D. Lister, R. Mathumo, I.N. Ross, M.J. Show, W.T. Toner, A.P. Visser, and B.E. Wyborn, J. Mod. Opt. **43**, No. 5, 1025–1033 (1996).
4. Yu.I. Bychkov, N.G. Ivanov, V.F. Losev, and G.A. Mesyats, Pisma Zh. Tekh. Fiz. **14**, Issue 6, 566–569 (1988).
5. E.N. Abdullin, S.I. Gorbachev, A.M. Efremov, B.M. Kovalchuk, S.V. Loginov, V.S. Skakun, V.F. Tarasenko, V.S. Tolkachev, A.V. Fedenev, E.A. Fomin, and P.M. Shchanin, Quant. Electron. **23**, No. 7, 564–567 (1993).
6. N.G. Ivanov, V.F. Losev, E.I. Naats, V.V. Ryzhov, I.Yu. Turchanovsky, and A.G. Yastremsky, Quant. Electron. **27**, No. 8, 670–672 (1997).
7. N.G. Ivanov, V.F. Losev, Yu.N. Panchenko, and A.G. Yastremsky, Quant. Electron. **29**, No. 10, 852–856 (1999).
8. E.N. Abdullin, D.M. Grishin, V.P. Gubanov, V.B. Zorin, A.A. Kim, B.M. Kovalchuk, E.V. Kumpyak, J. Liu, A.V. Morozov, V.S. Skakun, A.S. Stepchenko, V.F. Tarasenko, V.S. Tolkachev, N.V. Tsoy, and P.M. Shchanin, Quant. Electron. **34**, No. 3, 199–202 (2004).
9. G.A. Mesyats, V.V. Osipov, and V.F. Tarasenko, in: *Proc. SPIE* (Opt. Eng. Press, Washington, 1995), 374 pp.
10. B.M. Kovalchuk, V.F. Losev, G.A. Mesyats, and V.F. Tarasenko, Rus. Phys. J. **43**, No. 5, 352–357 (2000).
11. S.P. Bugaev, E.N. Abdullin, V.B. Zorin, B.M. Kovalchuk, S.V. Loginov, G.A. Mesyats, V.S. Skakun, V.F. Tarasenko, and P.M. Shchanin, Quant. Electron. **34**, No. 9, 801–804 (2004).
12. V.D. Zvorykin, S.V. Arlantsev, V.G. Bakaev, and A.A. Ionin, Laser and Particle Beams **19**, No. 5, 609–622 (2001).
13. E. Baksht, V.F. Losev, A.N. Panchenko, Yu.N. Panchenko, and V.E. Tarasenko, Proc. SPIE **4747**, 88–92 (2002).
14. I.N. Konovalov, V.F. Losev, L. Jingru, and Yu.N. Panchenko, Proc. SPIE **5483**, 55–59 (2004).
15. I.N. Konovalov, V.F. Losev, Yu.N. Panchenko, N.G. Ivanov, and M.Yu. Sukhov, Quant. Electron. **35**, No. 3, 237–240 (2005).