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Wide-aperture excimer laser system

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***Abstract*. An excimer laser system having an output aperture diameter of 40 cm and consisting of five lasers, three of which are excited by an electric discharge and the remaining two by an electron beam, is built. The first laser produces a 308-nm radiation with a duration of 200 – 250 ns, a spectral linewidth of 0.9 cm^{-1} and the beam divergence close to the diffraction limit. This pulse is amplified in the active media of the other lasers. As a result, radiation with an energy of 5 J, spectral linewidth 0.9 cm^{-1} and beam divergence 37 μrad is produced at the output of the third laser. The output energy of the entire system amounts to 330 J and the pulse duration is 200 – 250 ns.**

Keywords: *excimer amplifier, excimer laser system, pulse duration.*

1. Introduction

Laser systems based on halogenides of noble gases are the most powerful and efficient sources of coherent radiation in the UV spectral range. This is a unique tool that can be used for solving many fundamental and applied problems including inertial fusion, interaction of ultrahigh-intensity radiation with matter, generation of X-rays, acceleration of particles in ultrastrong electromagnetic fields, etc.

The highest-power excimer laser system existing at present is the Nike facility (USA) which generates radiation pulses with an energy up to 5 kJ and a FWHM of 240 ns (KrF molecule, $\lambda = 248$ nm) [1]. The output amplifier of this system has an aperture of 60 × 60 cm. The system has been designed and is used for solving problems associated with inertial laser fusion. It has been used for producing high-power nanosecond pulses and for studying their interaction with targets. The second-highest energy excimer laser facility SuperAshura was built in Japan [2]. The output amplifier of this system has an aperture of 61 cm. The system emits 248-nm, 240-ns pulses of energy up to 3.7 kJ. It is used in experiments on the formation of high-power nanosecond and picosecond pulses and their interaction with matter. The high-power Titania KrF laser system emits ~1-kJ, ~150-ns pulses and has the 42-cm apertute of the output amplifier [3]. It is used in experiments on the formation of high-power picosecond and femtosecond laser beams, and for studying their interaction with matter.

In Russia also, the research is underway for developing high-power excimer lasers and laser systems [4 – 12]. For example, the MELS-4k laser system with an output amplifier having an aperture of 25 × 25 cm, energy up to 200 J ($\lambda = 308$ nm) and a pulse duration of 250 ns was built at the Institute of High-current Electronics, Siberian Branch, Russian Academy of Sciences [6, 7]. XeCl lasers ($\lambda = 308$ nm) with an aperture of diameter 40 cm [8] and 60 cm [9 – 11] and generating pulses with energy up to 660 J and 1.9 kJ for a pulse duration of ~350 ns and 250 ns, respectively, were developed. A KrF laser system with the Garpun output module having an aperture of 16 × 18 cm and generating pulses of duration100 ns and energy 80 J was built at the Lebedev Physics Institute [12].

In this paper, we report the development and operation of a five-stage XeCl laser system with an output aperture of diameter 40 cm providing a high-quality output radiation up to 330 J in a pulse of duration ~250 ns. The first results obtained in experiments on this system are also presented.

2. Experimental setup and results

The laser system consists of five excimer lasers (Photon-1 – Photon-5), synchronisation and triggering systems, as well as matching optical elements. The working mixture is excited by an electric discharge in the first three lasers and by an electron beam in the remaining two. The laser radiation parameters were measured by traditional methods using standard equipment. The time and energy parameters of laser pulses were measured with a FEK-22 vacuum photodiode and TPI, IKT-2N, and OPHIR calorimeters with a L30A-EX measuring head. The signals were recorded with TDS oscilloscopes.

2.1 Electric-discharge lasers

Figure 1 shows the exterior view of the Photon-1 laser setup. It consists of a steel laser chamber of diameter 35 cm with the discharge gap electrodes mounted inside it. The electrodes are 107 cm long (active length 102 cm) and the electrode gap is equal to 4 cm. The laser chamber has a rectangular window closed by an insulator through which the discharge is fed. The insulator surface carries the

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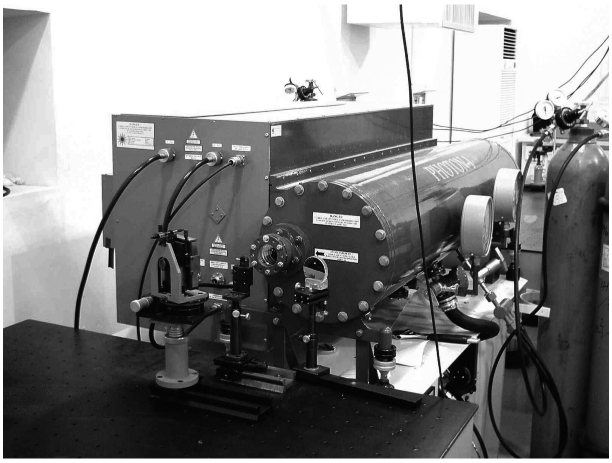

Figure 1. Photon-1 laser setup.

elements of the laser excitation system whose high-voltage components are enclosed in metal casing.

The discharge is excited by an electric circuit using an inductive energy storage system and a semiconductor current interrupter (formed by 12 SOS diodes) [13]. In such a circuit, the high-voltage pulse with a short leading front required for triggering the discharge is formed by using a peaking capacitor with $C = 3.2$ nF charged by the inductive energy storage system. Preionisation of the discharge is carried out automatically during charging of peaking capacitors by radiation from 90 spark gaps arranged uniformly on both sides of the anode. The main energy input to the active medium comes from the 550 nF storage capacitor charged to a voltage of 18 kV. The laser cavity is formed by mirrors with insulating coating having reflectivities of 100 % and 20 %. In mixtures Ne : Xe : HCl = 1520 : 10 : 1 at a pressure of 2 atm, the maximum laser energy was higher than 1.5 J with a pulse duration of 300 ns and a total efficiency of 1.35 % .

Two other electric-discharge lasers Photon-2 and Photon-3 [14, 15] have almost identical pump circuits and design. The external view of Photon-3 is shown in Fig. 2. The lasers consist of three main blocks including a gas-discharge chamber with a pump generator, an electric control panel, and a pneumatic control panel. The chamber contains the vacuum diode of the soft X-ray source, the electrodes forming the laser discharge gap, and an insulator for the high-voltage supply. The discharge electrodes are made of stainless steel, and the separation between the electrodes having a length of 80 cm and 100 cm for Photon-2 and Photon-3 is 5.4 cm and 9 cm, respectively. The X-rays are admitted into the discharge gap through a window closed by an 80-μm-thick titanium foil. The anode in the discharge gap is connected with the pump generator located outside the chamber through an insulator with the help of metallic studs. The design of the elements connecting the generator with the anode and inverse current leads ensures a low inductivity of the discharge circuit.

The vacuum diode of the X-ray source has a cylindrical casing containing the anode and the cold cathode working in the explosive electron emission regime. The cathode is made of plastic fibre-glass foil strips fastened to the spacer grid which is covered with a 40-μm-thick titanium foil to seal off the vacuum diode and to extract X-rays from it. A tantalum foil serves as the anode of the vacuum diode which is evacuated by an oil-vapour pump to a residual gas pressure of $\sim 10^{-4}$ Torr.

Figure 2. Photon-3 laser setup.

The vacuum diode is fed by a three-stage Arkad'ev–Marx generator with an impact capacitance of 15 nF connected to it through a KVI-120 high-voltage cable. A 50–55 kV positive pulse having a duration of 700 ns is supplied to the anode. The X-ray radiation dose in the cathode region of the discharge gap is 20–30 milliroentgen.

The main elements of the laser pump generator are a storage capacitor, a switch and a peaking capacitor. The storage capacitor C_1 consists of two (for Photon-2) or three (for Photon-3) parallel-connected FL-300 arrays. Each array has an electrical length of 300 ns, a capacitance of 150 nF, and a wave impedance of 1 Ω. The pulsed charging of the arrays is carried out with the help of an IK-300 capacitor C_3 which is connected to the arrays through a KVI-120 high-voltage cable and may be charged to voltages up to 40–65 kV. The 4.9-nF (for Photon-2) and 6.9-nF (for Photon-3) peaking capacitors, which are responsible for the formation of bulk discharge in the discharge gap, are assembled from KVI-3 ceramic capacitors (20 kV, 680 pF).

A multichannel rail discharger is used as the low-inductance switch. The anode is made of 1-mm-thick steel plate, while a rod of diameter 15 mm serves as the cathode. The electrodes are 80 (100)-cm long, and the gap between them is 4 (6) mm. A triggering electrode in the form of individual foil strips is mounted near the cathode along its length. The dischargers are triggered by a high-voltage pulse supplied to the cathode through spark gaps. The casing of the dischargers is made of an insulating tube of outer diameter 65 mm. In the working regime, the discharge gaps are filled with dry air under a pressure of 4–6.6 atm.

The high-voltage pulse for triggering all spark gaps is produced by a high-voltage pulse generator based on a TGI-1-1000/25 thyratron. Artificial radioengineering delay lines of the synchronisation system ensure a successive switching of the pump generator and the X-ray source.

Plane – parallel fused silica plates serve as the laser chamber windows. In the lasing regime, the laser cavity is formed by an outer dielectric mirror with 97 % reflectivity at a wavelength of 308 nm and a laser chamber window. The laser operates on a mixture of Ne, Xe and HCl gases under a total pressure of 3.5 – 4 atm.

In the free-running regime, Photon-2 and Photon-3 lasers generate 250 – 300-ns pulses with the energy up to 3.5 and 10 J, respectively.

2.2 Electron-beam-pumped lasers

Figure 3 shows the Photon-4 laser consisting of an Arkad'ev – Marx pulsed voltage generator (PVG), a vacuum diode, a laser chamber, the gas evacuation and filling system, and the electric control panel. The vacuum diode is fed directly from the generator installed in the same casing as the diode. Thus, vacuum insulation of the high-voltage part is ensured in the PVG. Such a construction allows a minimisation of not only the inductance of the vacuum diode power supply circuit, but also the size and weight of the accelerator. The PVG has three branches operating simultaneously and, as a result, its inductance and erosion of the discharge gap electrodes are lowered. The space with the spark gaps in each branch is filled with a mixture of dry air and SF_6, the capacitance of each stage in a branch is 0.18 nF. The accelerator is triggered by a controlled discharger in which the cable supplying a high voltage to the PVG is earthed. The discharger itself is actuated by a high-voltage pulse from a thyratron generator. The cathodes of the vacuum diode having a total length of 110 cm are mounted on a special holder fixed directly to the upper stage of the PVG.

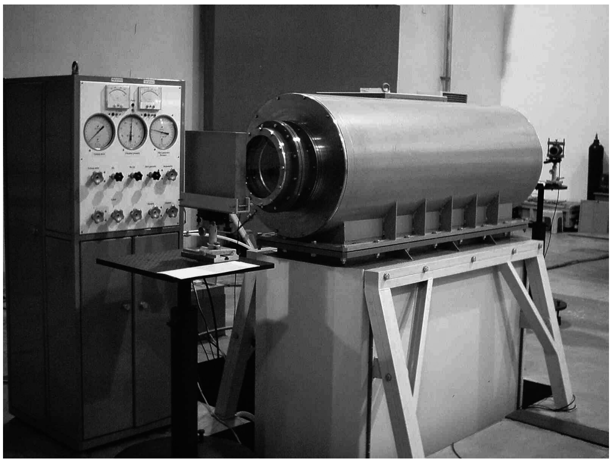

Figure 3. Photon-4 laser setup.

The laser chamber with an inner diameter of 25 cm is located between the cathodes at the middle of the vacuum diode and serves as the anode. The laser chamber is fixed to the diode casing along its length with the help of a metallic plate which improves the current flow and reduces the electron beam losses due to the effect of its intrinsic magnetic field. In the absence of this plate, the current closure occurs only through the endfaces of the gas chamber and the losses may amount to 50 %. Velvet is used as the emitter of electrons at the vacuum diode cathodes. The gap between the anode and the cathode is 7 cm. As a result, four radially converging beams are formed in the diode and are injected into the laser chamber through eight windows (two in each row) having a total length of 120 cm. Each window is sealed hermetically by a 40-μm-thick titanium foil mounted on a metal grid. A residual gas pressure of 5×10^{-5} Torr is maintained in the common casing for the PVG and the vacuum diode.

For a charging voltage of 85 kV, the generator forms at the vacuum diode a 1000 ns-voltage pulse with an amplitude up to 480 kV and a total current not exceeding 74 kA. The electron beam formed in the diode ensures a quite uniform excitation of the laser mixture.

Plane – parallel fused silica plates of diameter 300 mm serve as the laser chamber windows. In the lasing regime, the laser cavity is formed by the outer aluminium-sputtered mirror and the laser chamber window. The laser mixture consists of Ar, Xe and HCl gases. For an Ar : Xe : HCl = 1000 : 10 : 1 mixture at a pressure of 2 atm and a charging voltage of 85 kV, the radiation energy in the pulse reaches 120 J. The pulse FWHM is ~250 ns.

Figure 4 shows the Photon-5 laser. The gas mixture in the laser is excited by an electron beam converging radially from six sides [8]. The beam is formed in the vacuum diode containing 18 cathodes whose profile is chosen according to the results of numerical computation of beam parameters obtained by developing a binary code. The emitting cathode surface is made of velvet-covered carbonised fabric and graphite fibre material with a resistivity $(5 - 50) \times 10^{-2}$ Ω m. The emitting surface is 120 mm wide and the emitting cathodes have a total area of 0.95 m^2. The electrode spacing between the emitting surface and the supporting structure of the output window is 6 cm. The supporting structure has 18 windows (three in each row) with a total length of 150 cm. The geometrical transparency of the beam extraction system is ~75 %. The beam is extracted to the laser chamber through a 40 μm-thick Ti foil. The laser cell has a diameter of 41 cm and a volume of ~200 L.

The voltage pulse at the diode is formed with the help of two parallel-connected linear transformers with vacuum insulation of the secondary winding. The transformers consist of ten stages, each formed by eight IK-100-0.17 capacitors (100 kV, 0.17 μF, 50 nH). The output power of each stage is ~12 GW. The voltage is supplied to the diode

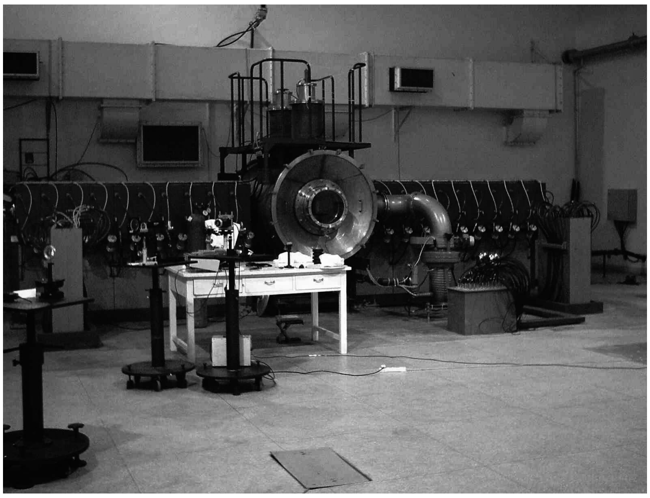

Figure 4. Photon-5 laser setup.

(at the cathode collector) through vacuum lines which simultaneously serve as secondary transformer windings. The vacuum diode chamber has a diameter of 131 cm and a length of 210 cm. The cathode collector is a cylinder of diameter 114 cm and length 120 cm, suspended coaxially with the vacuum chamber from two springs located in the upper part of the vacuum chamber. The vacuum system is pumped by two AVDM-250 vacuum units with nitrogen traps to a residual pressure of $(3-4)\times10^{-5}$ Torr in the diode.

For a charging voltage of 85 kV, the voltage pulse at the vacuum diode attains a peak of ~550 kV, the total current attains a value of 320 kA, and an energy of 87 kJ is supplied from the transformer to the diode. For a charging voltage of 80 kV, the voltage at the vacuum diode is ~440 kV, the total current is 290 kA and the energy supplied to the diode is 78 kJ. The energy supplied to the gas increases as the pressure rises up to 2.5 atm, after which it remains practically unchanged as the pressure increases to 3.5 atm. A maximum energy of ~ 19 kJ is supplied by the electron beam to the gas. The efficiency of the energy transfer from the primary accumulator to the gas is ~19 %, which is close to the value obtained in conventional water-cooled accelerators [1 – 3].

Plane – parallel fused silica plates of diameter 400 mm served as the laser chamber windows. The laser was tested in the lasing regime with a cavity formed by an aluminium-coated plane mirror and the laser chamber window. The working mixture consisting of Ar, Xe and HCl was prepared directly in the laser chamber. For an Ar : Xe : HCl = 760 : 20 : 1 mixture at a pressure of 2 atm and a charge voltage of 85 kV, the radiation energy in the pulse reached 660 J [8]. The pulse FWHM was ~350 ns. The nonuniformity in the radiation energy density distribution over the cross section of the laser beam did not exceed 10 %.

2.3 Laser system

Figure 5 shows the principal scheme of the synchronisation and triggering system used for a synchronous operation of the entire setup. The entire laser system was controlled by a personal computer which compiled instructions for the synchroniser providing voltage pulses with an amplitude of 600 V and a controlled delay between the pulses. These pulses were used for triggering four TG1 – TG4 thyratron generators and the magnetisation generator MG of the Photon-5 laser. The latter generates two magnetisation pulses which are supplied to the linear transformers and magnetise their cores in the appropriate direction before the beginning of the laser operation. The thyratron generators produce negative voltage pulses with an amplitude of ~20 kV which are supplied to trigger the spark gaps of Photon-1 – Photon-3, as well as to the input of the generators G4 and G5. Both generators produce negative voltage pulses with an amplitude of ~85 kV which are supplied to trigger the rail discharge switches of Photon-2 and Photon-3 and to trigger Photon-4, as well as to the input of the generators G1 and G2. The triggering generators form 40 negative voltage pulses with an amplitude of ~85 kV which trigger the dischargers of the transformer stages of Photon-5. The computer also regulates the synchronous switching on and off of the charging of storage capacitors of all lasers, thus making it possible to charge them at a particular instant of time.

Thus, the first stage of the laser system operation involves charging of the storage capacitors, the instant of whose switching is determined by the charging time of each of the Photons. At the next stage, a pulse is supplied to trigger the magnetisation generator of Photon-5. This is followed by pulses for triggering the thyratron generators of the first four Photons in a certain sequence, resulting in the final starting of the system.

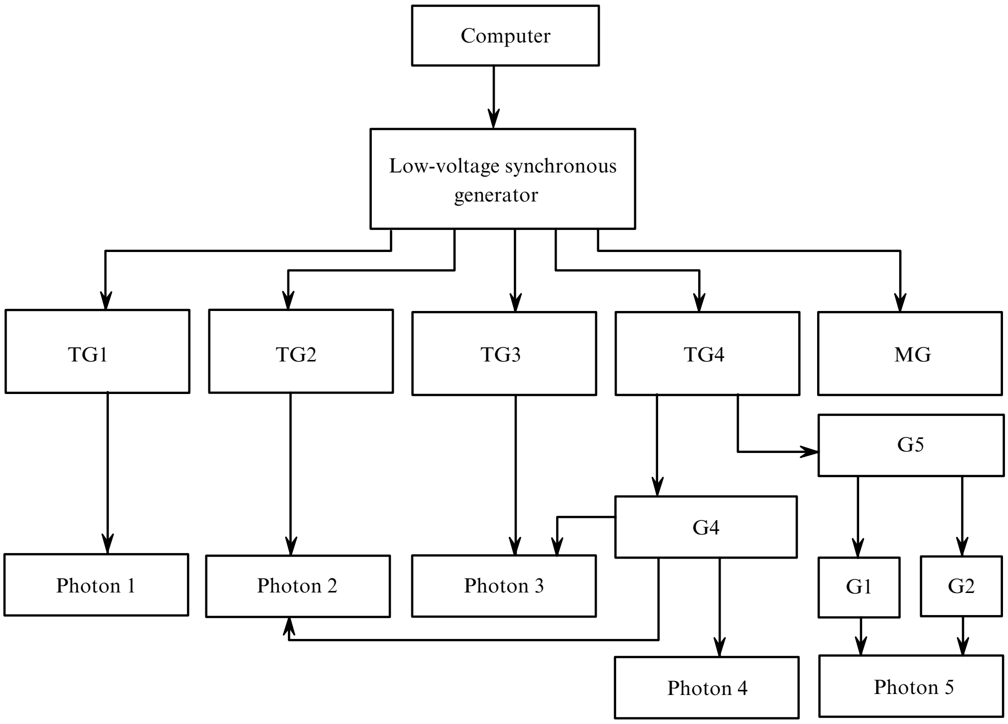

Figure 5. Block diagram of the synchronisation and triggering system.

All laser systems operate in the amplification regime. The laser chamber windows are tilted at a certain angle to rule out a feedback between them. The Photon-1 laser was used to produce the master oscillator MO [13] whose optical diagram allow the formation of a high-quality beam in a certain part of the active volume used for the MO. This beam is then amplified in another part of the active volume. Two diaphragms of diameter 2 mm minimise the divergence of radiation in the cavity. In this case, the Fresnel number N is ~ 2 for a 1.5-m-long cavity. The spectral selection was carried out with the help of a diffraction grating (1800 lines mm^{-1}) in the autocollimation regime. The feedback in the cavity is effected through the first diffraction order of the grating. To reduce the noise component in the output radiation, the laser beam is extracted through a translucent mirror with a reflectivity of 30 %. The low-power high-quality radiation from the MO is further amplified during the next two passes through the same active medium and gradually expanded to a diameter of 7 mm at the output. The resulting pulse from Photon-1 had an energy up to 50 mJ, a duration of 250 ns and a spectral linewidth of 0.9 cm^{-1}. The laser beam containg about 80 % of the energy had a divergence of 0.13 mrad, which is just 1.2 times larger than the diffraction limit.

This beam was expanded by a lens telescope of magnification $M = 1.5$ in such a way that the beam diameter matched with the size of the active media of Photon-2 and Photon-3. The beam was amplified in the active medium of Photon-2 in three passes and in the active medium of Photon-3 in a single pass. The beam diameter at the output from the amplifiers in this case was 3 and 6 cm, respectively. Subsequent matching of the beam diameter with the size of the active medium of the Photon-4 and Photon-5 amplifiers was carried out with the help of a lens telescope with $M = 5$. After expansion at the telescope, the beam was amplified during a single pass through the active medium of Photon-4 and in one or two passes through the active medium of Photon-5.

Table 1 shows the results of experiments carried out on the laser system. The highest radiation energy of 330 J was obtained in Photon-5 as a result of a single-pass amplification in the case of the minimum flux of amplified spontaneous emission (ASE) and minimum energy losses due to absorption of radiation in the active medium. A double-pass amplification leads to an enhancement of absorption as well as competition from ASE whose intensity increases due to reflection at the back mirror with $R = 99$ %. This lowers the amplified radiation energy to 250 J.

Table 1. Laser Radiation Parameters.

Lasers	Operation regime	Energy/J	Pulse duration/ns	Linewidth/cm^{-1}	Divergence/μrad
Photon 1	Generator	1.5	300	–	–
	MO	0.05	200 – 250	0.9	130
Photon 2	Generator	3.5	250	–	–
	Amplifier	0.5	200 – 250	0.9	60
Photon 3	Generator	10	300	–	–
	Amplifier	5	200 – 250	0.9	37
Photon 4	Generator	120	250	–	–
	Amplifier	40	200 – 250	–	–
Photon 5	Generator	660	350	–	–
	Amplifier	250, 330	200 – 250	–	–

The spectral and spatial parameters of radiation were recorded only for the first three devices. The divergence was measured from the size of the spot in the focal plane of the lens with a focal length $F = 13.5$ m, while the line width was measured with the help of a Fabry – Perot interferometer. The radiation intensity distribution was recorded in both cases with a CCD array. Measurements of the linewidth reveal that it remains unchanged after amplification and amounts to 0.9 cm^{-1}. On the whole, the divergence of amplified radiation decreases with increasing the beam diameter. However, it increases slightly relative to the diffraction limit probably due to distortions in the active medium and the optical path.

Figure 6 shows the output energy of the main amplifier as a function of the input energy. The input energy was varied by switching off one of the amplifiers (Photon-3 or Photon-4). One can see that saturation of the Photon-5 amplifier occurs only when all the amplifiers are switched on, the gain in this case being equal to 10. The autograph of the laser beam recorded on photographic paper has a fairly uniform distribution with diffraction rings at various inhomogeneities of the optical path, which points towards a high spatial coherence of the output radiation.

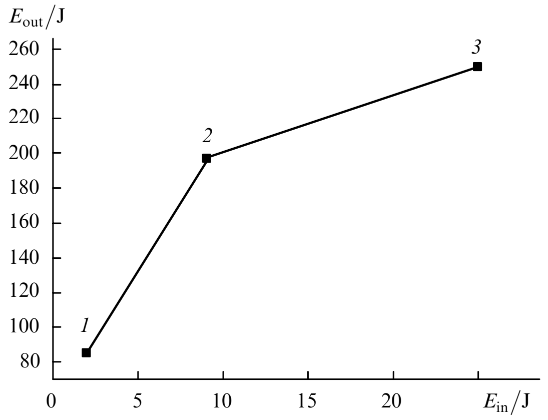

Figure 6. Dependence of the output energy of the Photon-5 laser with double-pass amplification on the energy of the input signal formed by switching on Photon-1 and Photon-3 (*1*), Photon-1, Photon-2 and Photon-4 (*2*), and Photon-1 – Photon-4 (*3*).

3. Conclusions

We have reported the development of an excimer laser system with an output aperture of diameter 40 cm and a radiation energy up to 330 J. The system allows the formation of laser radiation pulses with a linewidth of 0.9 cm^{-1} and a small divergence. The output radiation pulse duration is 200 – 250 ns. Each stage of the system may work as a generator of laser pulses with an energy 1.5 – 660 J and a duration of 200 – 350 ns.

It is proposed to use this system for experimental investigations on the formation of laser radiation pulses with different parameters and on the interaction of high-power laser radiation with matter.

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