PACS numbers: 42.55.Lt; 42.60.Fc; 52.38.Ph; 52.57.–z
DOI: 10.1070/QE2009v039n08ABEH013993

Laser stand for irradiation of targets by laser pulses from the Iskra-5 facility at a repetition rate of 100 MHz

V.I. Annenkov, S.G. Garanin, V.A. Eroshenko, N.V. Zhidkov, A.V. Zubkov, S.V. Kalipanov
N.A. Kalmykov, V.P. Kovalenko, V.A. Krotov, S.G. Lapin, S.P. Martynenko, V.I. Pankratov,
V.S. Faizullin, V.A. Khrustalev, N.M. Khudikov, V.S. Chebotar'

***Abstract*. A train of a few tens of high-power subnanosecond laser pulses with a repetition period of 10 ns is generated in the Iskra-5 facility. The laser pulse train has an energy of up to 300 J and contains up to 40 pulses (by the 0.15 intensity level), the single pulse duration in the train being ~ 0.5 ns. The results of experiments on conversion of a train of laser pulses to a train of X-ray pulses are presented. Upon irradiation of a tungsten target, a train of X-ray pulses is generated with the shape of an envelope in the spectral band from 0.18 to 0.28 keV similar to that of the envelope of the laser pulse train. The duration of a single X-ray pulse in the train is equal to that of a single laser pulse.**

Keywords: *high-power laser facility, laser pulse train, conversion of laser radiation to X-rays.*

1. Introduction

The Iskra-5 facility consists of a high-power twelve-channel photodissociation iodine laser emitting at 1.315 μm [1] and a number of target chambers equipped with a focusing optics and diagnostic means. The scope of investigations on the interaction of laser radiation with matter performed with the help of this facility is quite broad [2 – 9]. However, all previous studies were performed by using the regime of single short laser pulses, when a target (or each of the two targets [8]) was irradiated by one laser pulse and the difference ±50 ps between the arrival times of pulses from different laser channels to the same target is much smaller than the laser pulse duration (~ 0.5 ns) [10].

However, a number of investigations require a different irradiation regime, when a target is exposed to a train of a few tens of subnanosecond pulses with a repetition period of ~ 10 ns. We call this regime the 100-MHz irradiation of a target. Such a regime was achieved in the Iskra-5 facility. It is provided first of all by a master oscillator (MO) operating in the active mode locking regime.

2. Master oscillator of the laser stand

As a MO for the 100-MHz target irradiation regime, we used one of the two standard MOs [8] of the Iskra-5 facility.

The standard MO of the Iskra-5 facility is an oscillator with active mode locking performed by the external modulation of cavity losses by an acoustooptic modulator operating in the standing wave regime. The MO cavity of length 1.5 m is formed by a highly reflecting spherical mirror with the radius of curvature $R \approx 5$ m and a flat mirror with the reflectance 50 %. An aperture of diameter 3 mm mounted in front of the spherical mirror provides the generation of the fundamental transverse cavity mode. The 50-MHz crystal quartz acoustooptic modulator is mounted in front of the flat mirror. A laser cell of active length 500 mm has the inner diameter 10 mm. Pumping is performed by a xenon coaxial lamp formed by the laser cell and a quartz tube with the external diameter 25 mm. The windows of the laser cell oriented at the Brewster angle provide linearly polarised radiation. The lamp is powered from an IK50-3 capacitor via a low-inductance gap. The duration of the first half period of the pump current is 6 μs. The decay in the power supply circuit of the pump lamp is close to the critical one, the logarithmic decay decrement is $\delta \approx 2.8$ and is almost independent of voltage.

The master oscillator generates a train of equidistant light pulses with a repetition period of 10 ns. The number of pulses in the train does not exceed, as a rule, 12 – 15. The envelope of the pulse train has a nearly Gaussian shape. An increase in the number of pulses in the train in the standard MO operation regime is unsuitable because this would reduce the energy contained in the central pulse of the train, which is cut off from the train and is directed to a circuit of amplifiers of the facility. Lasing in the MO appears in the standard regime close to the instant of passing the discharge current in the pump lamp through zero, i.e. a train of pulses appears within approximately 6 μs after the pumping onset. The divergence of radiation measured by the far-field radiation energy distribution is $\theta = 1.35$ mrad at the 0.82 level.

The master oscillator operates in the so-called amplification switching regime. This regime has the following mechanism. When the pump rate is high and the rates of the development of amplification and lasing are comparable, the inverse population accumulated during the development of lasing considerably exceeds the threshold population. As a result, a high-power pulse is generated, which resembles a giant pulse generated in the Q-switching regime. The laser pulse duration in the amplification switching regime is

---

V.I. Annenkov, S.G. Garanin, V.A. Eroshenko, N.V. Zhidkov, A.V. Zubkov, S.V. Kalipanov N.A. Kalmykov, V.P. Kovalenko, V.A. Krotov, S.G. Lapin, S.P. Martynenko, V.I. Pankratov, V.S. Faizullin, V.A. Khrustalev, N.M. Khudikov, V.S. Chebotar' Russian Federal Nuclear Center, All-Russian Research Institute of Experimental Physics, Institute of Laser Physical Studies, prosp. Mira 37, 607190 Sarov, Nizhnii Novgorod region, Russia; e-mail: annenkov@iskra5.vniief.ru

Received 27 October 2008; revision received 8 April 2009
Kvantovaya Elektronika **39** (8) 719 – 722 (2009)
Translated by M.N. Sapozhnikov

mainly determined by the cavity length, the active medium length, and the pump rate [11]. In fact, this mechanism of amplification switching determines the duration of the envelope of the pulse train formed due to active mode locking and, hence, the number of pulses in the train. Because the cavity length of the available MO provides the required pulse repetition period of 10 ns in the train, while the length of the active medium is specified by the cavity design, the only parameter that we can vary to increase the number of pulses in the train is the pump rate.

To study the influence of the pump rate on lasing parameters, we simulated the lasing process taking into account that in the case of the accurate adjustment of the Q-switching period, the shape of a train of mode-locked pulses virtually coincides with the shape of a free-running laser pulse when the Q switch is open because the Q switch is always open at the instant of propagation of train pulses through it [12]. Therefore, if we are interested only in the shape of the train, it is sufficient to simulate the free-running regime.

The system of cavity-length-averaged rate equations for the population difference N of working levels and the photon density M in the cavity in the two-dimensional approximation can be written in the form

$$\begin{aligned} \dot{N} &= -\frac{3}{2}\sigma NcM + H(t), \\ \dot{M} &= \left(\mu\sigma Nc - \tau^{-1}\right)M, \end{aligned} \tag{1}$$

where σ is the stimulated emission cross section; c is the speed of light; μ is the cavity filling factor; $\tau = 2L\times[c\ln(R_1R_2)^{-1}]^{-1}$ is the photon lifetime in the cavity; L is the cavity length; R_1 and R_2 are the reflectances of cavity mirrors; and $H(t)$ is the pump rate, which is assumed constant in calculations.

It was assumed that the initial instant of time corresponds to the moment of the lasing threshold achievement. The pump rate was varied in calculations. Figure 1 presents the results of numerical simulation of the dependences of the duration (at the 0.5 level) of the envelope of the pulse train and the energy of the first generated train on the pump rate in the MO with the parameters $L = 1.5$ m, $R_1 = 0.9$, $R_2 = 0.5$, $\mu = 0.33$, $\sigma = 1.38\times10^{-19}$ cm^2 (the pressure of the working mixture containing the SF_6 buffer gas was 4 atm) under the initial conditions $N = 0$ and $M = 10^{-10}$ cm^{-3}.

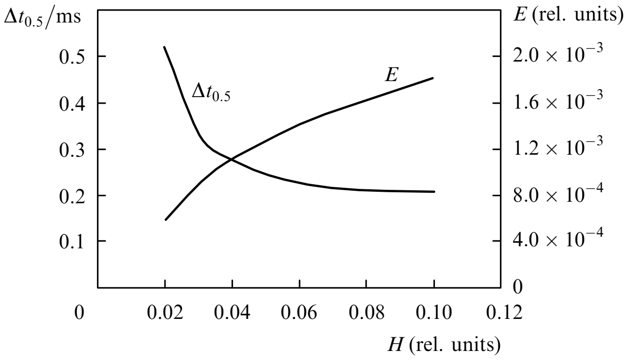

Figure 1. Calculated dependences of the envelope duration $\Delta t_{0.5}$ and energy E of the laser pulse train on the pump rate H.

The dependences presented in Fig. 1 show that a noticeable increase in the laser pulse duration (the train envelope) occurs only at the lowest pump rates, which corresponds in experiments to a small excess over the lasing threshold. As the pump rate is decreased, the laser pulse duration increases while the pulse energy decreases. Thus, by decreasing the pump rate, we can elongate a pulse train within certain limits.

The pump rate can be decreased by decreasing the pump energy supplied to the lamp or increasing the pump duration. However, the possibilities of decreasing the pump rate are limited because optical inhomogeneities appear in the lasing volume during long lasing development times, resulting in the deterioration of the laser radiation divergence [13]. In addition, when the pump rate approaches the threshold value, a poor reproducibility of the parameters of a generated pulse should be expected. Our investigations showed that the laser radiation divergence in a laser cell of diameter 10 mm with the sulphur hexafluoride buffer gas was not deteriorated at least for 9 μs after the pumping beginning.

We studied the two modifications of the standard MO. In the first modification, the first half period of the pump current was increased up to 9 μs by changing the length of a supply cable, while in the second modification the half period was increased up to 18 μs by changing the capacitance of a pump capacitor and using a laser cell of a larger diameter (20 mm).

In both cases the pressure of the ($i\text{-}C_3F_7I : SF_6 = 1:45$) working mixture in the laser cell was 4 atm, while a pulse duration in a train was ~ 0.5 ns, in good accordance with calculations [14]. In addition, a system for single pulse selection used in the standard MO was replaced by a Faraday gate to isolate optically the MO from a chain of subsequent amplifiers.

Our investigations have shown the principal possibility of generating a train of laser pulses containing up to 58 – 60 pulses at the 0.15 level in the first MO modification and up to 90 – 100 pulses in the second modification. However, to obtain trains of such a duration, the charging voltage across the pump capacitor should be maintained close to the threshold value. As a result, small variations in the initial conditions (often uncontrollable) caused noticeable changes in the duration of a generated train and in its energy and appearance time, and even could lead to quenching of lasing.

When the pump energy was still close to the threshold but already sufficient for the reliable reproduction of the parameters of the generated train from experiment to experiment, the number of pulses in the train was 25 – 30 for the first MO modification and 50 – 60 for the second one. Figure 2 presents the experimental dependence of the train duration on the pump energy, which uniquely determines the pump rate when its duration is fixed. Figures 1 and 2 show that experimental results are in good agreement with numerical simulations.

3. Amplification of a pulse train

A pulse train generated by the MO was amplified in a preamplifier stage (PAS) and was directed through a system of translating mirrors to one of the channels of the Iskra-5 facility described in [1, 10]. The amplifying channel contained three amplifiers A1, A2, and A4. Between amplifiers

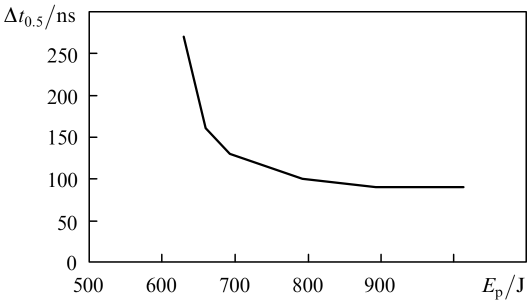

Figure 2. Experimental dependence of the laser pulse train duration on the pump energy.

were placed saturable 1067 dye absorbers with the initial transmission ~ 1 %. The parameters of the amplifiers are presented in Table 1.

Table 1. Parameters of the amplifying circuit of the Iskra-5 facility.

Amplifier	Active length/m	Working aperture diameter/mm	Energy capacity of a capacitor battery/kJ	Working mixture composition (total pressure 1 atm)
PAS	0.9	16	15	25 Torr i-$C_3F_7I + SF_6$
A1	1	35	34	35 Torr i-$C_3F_7I + SF_6$
A2	2	80	100	15 Torr i-C_3F_7I + Ar
A4	8	300 × 300	3400	2.5 Torr i-C_3F_7I + 367 Torr Ar + CO_2

We obtained in experiments at the channel output the trains of laser pulses of energy up to 300 J containing up to 40 pulses (at the 0.15 level), the single pulse duration being ~ 0.5 ns.

Figure 3 demonstrates the oscillogram of a 170-J pulse train containing 39 pulses (at the 0.15 level).

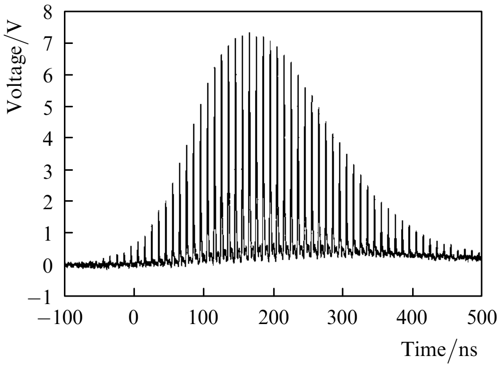

Figure 3. Oscillogram of the 170-J pulse train containing 39 pulses (over the 0.15 level).

Due to the gain saturation during train amplification, the train noticeably 'rolls over' forward. Thus, during amplification in the first amplification stage with the small-signal gain ~ 1000, the 'rolling over' time was a few tens of nanoseconds.

4. Experimental results

In conclusion, we present short experimental results on the conversion of a train of laser pulses to an X-ray train. We used in these experiments only amplifier A1, and radiation was focused on a tungsten target. The laser radiation intensity was $7 \times 10^9 - 1 \times 10^{11}$ W cm^{-2}. A train of laser pulses was detected with a Thorlabs SIRS-FC photodiode with the 5-GHz passband. X-rays were detected with vacuum X-ray diodes with stainless steel cathodes. The X-ray diodes were placed behind filters manufactured of materials which determined the detection range. The output signals of diodes were measured with a 6-GHz oscilloscope.

Figures 4 and 5 present the oscillograms of signals detected in one of the experiments on the conversion of laser radiation to X-rays. Figure 4 shows a train of laser pulses (28 pulses at the 0.15 level). The duration of a single pulse in the train is $\tau_{0.5} = 0.56 \pm 0.05$ ns and the total energy of the pulse train is $E = 7.0 \pm 1.4$ J. Figure 5 presents the oscillogram of a signal detected with an X-ray diode with a 1-μm-thick Dacron filter (the 0.18 − 0.28-keV detection range). The envelope of the train of X-ray pulses retains the shape close to that of the envelope of the train of laser pulses. The duration of single X-ray pulses was $\tau_{0.5} = 0.56 \pm 0.05$ ns; no distortions of the pulse shape within the train were detected.

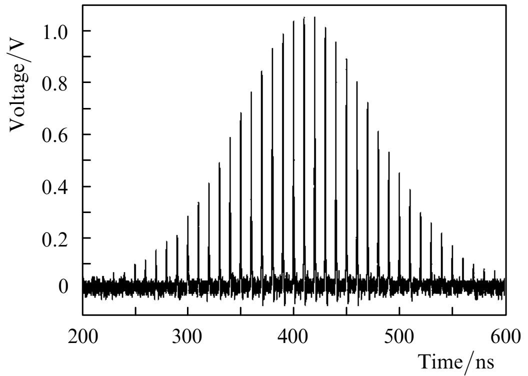

Figure 4. Oscillogram of a laser pulse train.

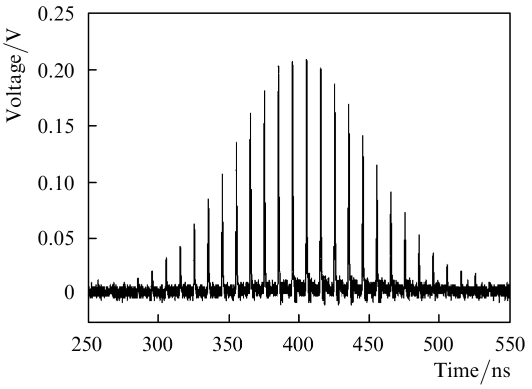

Figure 5. Oscillogram of an X-ray pulse train.

Thus, we have obtained the regime of 100-MHz irradiation of targets in which a target is irradiated by a train of a few tens of subnanosecond pulses with a repetition period of 10 ns. The number of pulses in the train at the 0.15 level is 40. The total energy of pulses in the train achieves 300 J. By irradiating a tungsten target, we obtained a train of X-ay pulses with the envelope shape in the spectral band from 0.18 to 0.28 keV similar to that for laser pulses. The duration of a single X-ray pulse in the train is equal to that of a laser pulse.

References

1. Annenkov V.I., Bagretsov V.A., Bezuglov V.G., et al. *Kvantovaya Elektron.*, **18**, 536 (1991) [*Sov. J. Quantum Electron.*, **21**, 487 (1991)].
2. Bessarab A.V., Gaidash V.A., Dolgoleva G.V., et al. *Zh. Eksp. Teor. Fiz.*, **102**, 1800 (1992).
3. Abzaev F.M., Annenkov V.I., Bezuglov V.G., et al. *Pis'ma Zh. Eksp. Teor. Fiz.*, **58**, 28 (1993).
4. Bel'kov S.A., Bessarab A.V., Vinokurov O.A., et al. *Pis'ma Zh. Eksp. Teor. Fiz.*, **67**, 161 (1998).
5. Bel'kov S.A., Bessarab A.V., Veselov A.V., et al. *Zh. Eksp. Teor. Fiz.*, **114**, 837 (1998).
6. Bel'kov S.A., Abzaev F.M., Bessarab A.V., et al. *Laser Part. Beams*, **17** (4), 591 (1999).
7. Bogunenko Yu.D., Bessarab A.V., Bondarenko G.A., et al. *Fiz. Plazmy*, **31**, 765 (2005).
8. Annenkov V.I., Bezuglov V.G., Bessarab A.V., et al. *Kvantovaya Elektron.*, **36**, 508 (2006) [*Quantum Elektron.*, **36**, 508 (2006)].
9. Bessarab A.V., Garanin S.G., Martynenko S.P., et al. *Dokl. Ross. Akad. Nauk*, **411**, 609 (2006).
10. Annenkov V.I., Bespalov V.I., Bredikhin V.I. *Kvantovaya Elektron.*, **35**, 993 (2005) [*Quantum Elektron.*, **35**, 993 (2005)].
11. Holla C., Compa C., in *Handbook of Chemical Lasers*, R.W. Gross, J.F. Bott (Eds) (New York: Wiley, 1976; Moscow: Mir, 1980).
12. Baker Y.J., King T.A., McNaught W.G. *J. Phys. D: Appl. Phys.*, **12**, 997 (1979).
13. Brederlov G., Fill E., Vitte K. *Moshchnyi iodnyi lazer* (High-power Iodine Laser) (Moscow: Atomizdat, 1985).
14. Kuizenga D.J. *IEEE J. Quantum Electron.*, **17** (9), 1694 (1981).