

# Problem of nuclear-laser power engineering and methods of their solution\*

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## Abstract

The concept of a high power reactor-laser system based on a nuclear pumped optical quantum amplifier (OKUYaN) was formulated at IPPE in the mid-1980-ies. The idea amounted to the use of wide-aperture OKUYaN as an amplifier within the already well-known “master laser – two-pass amplifier with phase conjugation” scheme.

The structure of such an amplifier includes a system of two neutron-coupled units – an ignition reactor (RB) and a nuclear pumped laser amplifier (LB). The ignition unit is a compact multi-core pulsed fast neutron reactor. The laser amplifier unit operates on thermal neutrons and, with regard to the neutronics, it is a subcritical booster zone of the ignition reactor unit.

Unique reactor-laser complex incorporating demonstration sample of a pulsed reactor-laser system based on OKUYaN (test facility “Stand B”) having no analogues anywhere in the world, was developed and put into operation at IPPE in 1999 for the purpose of substantiation of basic principles of the OKUYaN concept and demonstration of the possibility of its practical implementation, as well as verification of calculation codes and development of relevant equipment elements.

Problems overcome in the development and construction of “Stand B” test facility, the choice and justification of the neutronics and laser characteristics of the OKUYaN demonstration sample are discussed in the present paper. Provided are the results of a detailed computational-experimental study of the demonstration sample characteristics, the data from systems studies of direct conversion of nuclear fission energy into laser radiation energy in complex reactor-laser devices and the results of examination of prospects for the development of nuclear-laser power engineering.

## Keywords

Multi-core nuclear reactor, neutrons, fission fragments, nuclear pumping, laser, optical quantum amplifier with nuclear pumping

## 1. Introduction

Generation of nuclear excitation plasma, i.e. the state of the matter emerging during deceleration in it of products of nuclear reactions as the result of excitation and ioni-

zation of atoms, is the primary process of interaction of charge nuclear reaction products with matter.

Recombination non-equilibrium represents an important specific feature of nuclear excitation plasma. This means that inverse density of population of quantum

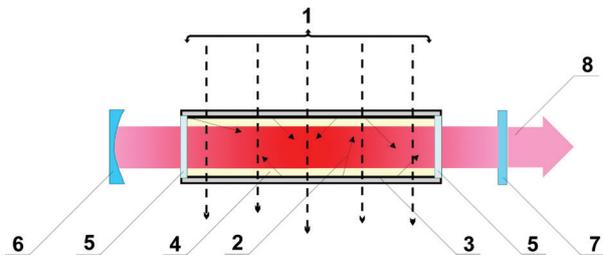
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levels of its components develops in the process of relaxation of such plasma, i.e. the necessary conditions for direct conversion of energy from nuclear reactions into laser radiation energy are satisfied. The device, in which such direct conversion is achieved, is called direct nuclear pumped laser (NPL). Design and principle of operation of such device is easy to understand using the example of one of the simplest NPL types, layout of which is presented in Fig. 1. Charged products of nuclear reaction emitted as the result of interactions of neutrons with nuclei of neutron-active coating matter escape from the latter and decelerate in gaseous laser-active medium filling the laser tube (laser-active element – LAEL) generating in the tube nuclear-excitation plasma and, consequently, inverse population of one of its components, i.e. are “pumping” the laser. Energy accumulated in the inversion is extracted from the LAEL in the form of laser beam using optical resonator consisting of non-transmitting and semi-transmitting mirrors.

Until recently, investigation of nuclear pumped lasers was conducted in a number of laboratories in Russia (RFNC VNIIEF, SSC RF – IPPE, RFNC VNIITF, Prokhorov General Physics Institute, MEPHI), USA (Sandia National Laboratories, University of Illinois, NASA Langley Research Center, Los Alamos National Laboratory, University of Missouri – Columbia and others), Germany (Technische Universität München) and China (Institute of Nuclear Physics and Chemistry of CAEP). Seven scientific conferences on different levels dedicated to the subject in question were held and five monographs were published (Gulevich et al. 2003, Karelin 2007, Melnikov et al. 2008, 2015, Prelas 2016).

By the present moment laser generation was obtained in nuclear pumping of about thirty different gaseous laser-active media with products of different nuclear reactions including  $^{10}\text{B}(n,\alpha)^7\text{Li}$ ,  $^6\text{Li}(n,\alpha)^3\text{T}$ ,  $^3\text{He}(n,p)^3\text{T}$ ,  $^{235}\text{U}(n,f)$  and others. (Gulevich et al. 2003, Karelin 2007, Melnikov et al. 2008, 2015, Prelas 2016). It is evident that the most efficient reaction of fission of U-235 nuclei is the most efficient one for laser pumping. It is characterized with the highest energy yield among neutron nuclear reactions (about 200 MeV), high thermal neutron cross-section ( $\sim 500$  barn) and it is a chain reaction. About 80% of energy yielded in this reaction is carried away by two fission fragments, which are heavy ions with average charge of about 20 charge units, kinetic energy of about 85 MeV and mass of about 120 amu.

When sufficiently large amount of uranium-containing LAEL and neutron moderating materials are assembled to form the unified compact system the latter begins to multiply neutrons and may become critical or close to criticality. Such systems are called the reactor-laser systems. The interest to these systems is explained by the unique properties of the nuclear reactor as the source of laser pumping, such as its high-energy capacity, compactness and self-sufficiency. Thanks to the high penetrative capacity of neutron in neutron-multiplying media, the possibility emerges to pump laser-active media in practi-



**Figure 1.** Principal layout of nuclear pumping laser: 1 – neutron beam; 2 – nuclear reaction products; 3 – neutron-active substance; 4 – laser-active substance; 5 – optical windows; 6, 7 – resonator; 8 – laser radiation.

cally unlimited volumes. All the above opens the perspective for the development of super-powerful, compact and autonomous sources of laser energy, i.e. the development of principally new direction of the use of nuclear energy – nuclear laser power generation necessary for implementation of a whole series of the newest laser technologies, for instance, such technologies as the inertial thermonuclear fusion, beam power generation, power supply and launching space missions, remotely controlled deep cutting and welding, energy intensive chemical synthesis, isotopic separation, 3D metal ceramics lithography and many others.

Two approaches to the development of powerful reactor-laser systems are known as of today. The first approach (Walters et al. 1979) is based on the combination of the zone of pumping laser-active medium with core of a stationary thermal nuclear reactor. Corresponding device was given the name “reactor-laser” and represents a powerful continuous (quasi-continuous) source of laser radiation. In the second approach (McArthur et al. 1977), the uranium-containing laser pumping zone and the reactor core are separated from each other functionally and spacially. Pumping area surrounds the reactor core, which is subcritical as pertains to the neutronics and represents the booster zone of the pulsed nuclear reactor. Such device was given the name “laser with pumping from pulsed nuclear reactor” and is the powerful source of pulsed laser radiation.

The concept of powerful reactor-laser system based on the optical quantum amplifier with nuclear pumping (OKUYaN) was formulated in 1986 at the SSC RF – IPPE (Dyachenko 1996). The idea of the system amounts to the use of wide-aperture OKUYaN as the amplifier in the well-known layout of the “master laser – two-pass amplifier with phase conjugation”. Wide-aperture OKUYaN consists of two main units – reactor (ignition) unit RU and laser unit LU. It is suggested to use pulsed multi-core fast reactor as the ignition reactor. Laser unit is operated on thermal neutrons and represents the subcritical booster core of the ignition reactor.

It is fairly easy to demonstrate that in ideal (limiting) case of one neutron undergoing leakage per one fission event in the RU when the direct neutron coupling  $\text{RU} \rightarrow \text{LU}$  reaches maximum (fission in the laser unit is initiated with probability close to unity by neutron escaping from

the reactor unit), the inverse LU → RU neutron coupling is missing and  $\Delta t_{1/2}^{RU} \leq \tau_{LU}$ , it follows from the definitions of the neutron multiplication factor  $k_{eff}^{LU}$  and neutron lifetime  $\tau_{LU}$  in the laser unit that

$$E_{LU} = E_{RU} / (1 - k_{eff}^{LU}) \nu; \quad (1)$$

$$\Delta t_{1/2}^{LU} = -0.7 \tau_{LU} / \ln k_{eff}^{LU}, \quad (2)$$

where  $E_{LU}$ ,  $E_{RU}$  is the energy released in the LU and RU, respectively;  $\nu$  is the average number of prompt fission neutrons;  $\Delta t_{1/2}^{RU}$ ,  $\Delta t_{1/2}^{LU}$  is the energy release pulse width at half maximum in the RU and LU, respectively.

It follows from the above that for parameters realistic as of today  $E_{RU} = 15$  MJ,  $k_{eff}^{LU} = 0.95$ ,  $\tau_{LU} = 100$   $\mu$ s,  $\nu = 2.45$  and the efficiency of conversion of fission energy into laser radiation energy equal to ~1% we obtain the value of laser energy equal to ~1.2 MJ with duration at half maximum of the pumping pulse ~1.3 ms.

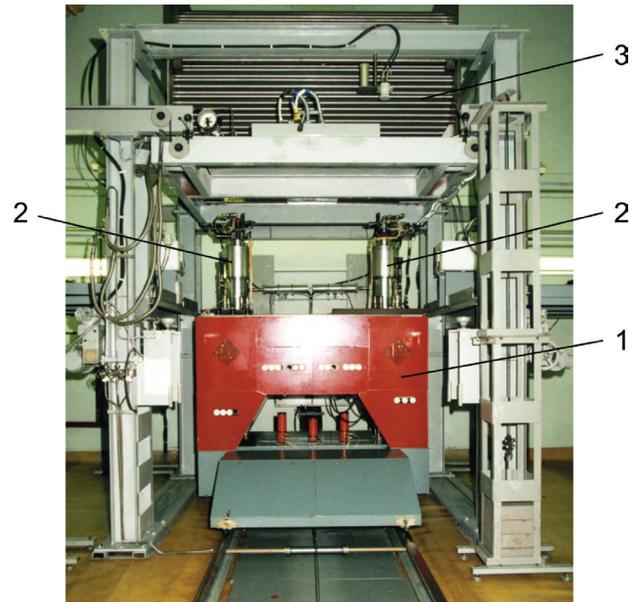
Unique reactor-laser complex “Stand B” - demonstration sample of the OKUYaN reactor-laser system having no analogues anywhere in the world, was developed and put into operation at IPPE in 1999 for the purpose of practical demonstration of feasibility of the OKUYaN concept, as well as verification of calculation codes and working out relevant hardware elements. (Dyachenko et al. 2000).

Brief description of the design of the device and results of experimental investigation of neutronics and laser characteristics of the demonstration sample of the reactor-laser system based on the OKUYaN concept (“Stand B”), as well as the development methods for upgrading the pilot facility for the purpose of increasing energy and power of the laser beam are discussed below.

Main results presented in the paper were published in the reference sources and are patented (Dyachenko and Fokin 2012a, Dyachenko et al. 1997).

## 2. “Stand B” – SSC RF – IPPE reactor laser complex

Picture of the “Stand B” OKUYaN is presented in Fig. 2. Bars-6 two-core self-quenching pulsed fast reactor developed at the RFNC-VNIITF (Levakov et al. 2002) and upgraded at IPPE taking into account its operation in the composition of reactor-laser system was used as the ignition reactor. Reactor cores (RC) are fabricated from uranium-molybdenum alloy (mass fraction of Mo – 9%). Uranium enrichment with  $^{235}\text{U}$  isotope – 90%.  $^{235}\text{U}$  mass in each of the cores – 105 kg. In terms of design, the RU represents a cylinder with 226-cm diameter and 232-mm height assembled from rings on the central steel pipe. Reactor cores are installed on the platform moving along the rails laid in the test facility room. One of RCs is movable and can be shifted relative to the second core in such a way that the distance between them can vary within the limits from 340 to 1500 mm.



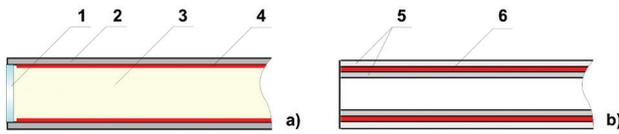
**Figure 2.** Pilot OKUYaN facility: 1 – Bars-6 reactor; 2 – reactor cores; 3 – laser unit.

Each of the cores is equipped with controls that allows to control the reactor when it is in criticality for delayed neutrons, and also very quickly (with a speed of up to  $220 \beta_{eff}/s$ ) put the reactor in supercriticality for instantaneous neutrons to generate a pulse and return by the end of the pulse at a speed of about  $200 \beta_{eff}/s$  from the critical state at delayed neutrons to the state of deep subcriticality (up to  $-20 \beta_{eff}$ ). Transition of the reactor from the conditions of instantaneous supercriticality to the conditions of delayed criticality in the process of pulse generation takes place automatically due to the negative temperature reactivity factor.

Test stand is designed in a way allowing the reactor performing alternately the following two functions. Firstly, generating neutron burst for irradiating not neutron-multiplying elements of laser unit hardware on the first workplace (WP) corresponding to Phase 1 of the test facility put into operation in 1996. Secondly, it can serve as the ignition reactor unit during operation with neutron-multiplying laser unit in the composition of the OKUYaN test sample on the second WP constituting Phase 2 of the test facility put into operation in 1999.

Laser unit represents cylindrical structure with 2.5-m length and 1.7-m diameter with lateral cavity for arrangement of ignition reactor cores. Laser unit is assembled from standard elements of the following five types: laser-active element (LAEL), LAEL imitator, element of inter-tubular neutron moderator, element of neutron reflector and the power multiplication channel (PMC). Arrangement of elements in the LU is determined by the loading map.

LAEL and its imitator are the main elements of the LU (Fig. 3). LAEL is the thin-walled (0.5 mm) stainless steel tube with 49-mm diameter and 2.5 m length covered from the inside with uranium metal coating (uranium mass – 40 g, enrichment with  $^{235}\text{U}$  isotope – 90%) with 5- $\mu$ m thickness hermetically sealed from both butt ends by clarified quartz windows and filled with laser-active medium.



**Figure 3.** Design of LAEL (a) and its imitator (b): 1 – optical window; 2 – thin-walled stainless steel tube; 3 – laser-active medium; 4 – uranium metal coating; 5 – aluminum tubes; 6 –  $U_3O_8$ .

LAEL is made in the form of aluminum tubes inserted one inside the other with outer diameter equal 49 mm and total wall thickness of 2.5 mm with narrow gap between the tubes filled with uranium dioxide. The imitator represents the exact neutronics copy of the LAEL, i.e. it contains exactly the same quantity of  $^{235}U$  (36 g) and has approximately the same properties with regard to neutron capture and scattering. This was designed in order to simplify the task of scaling the laser beam energy reduced in this case to the replacement of required number of imitators with LAEL with parameters of the pumping pulse in the arbitrary point of the LU remaining the same.

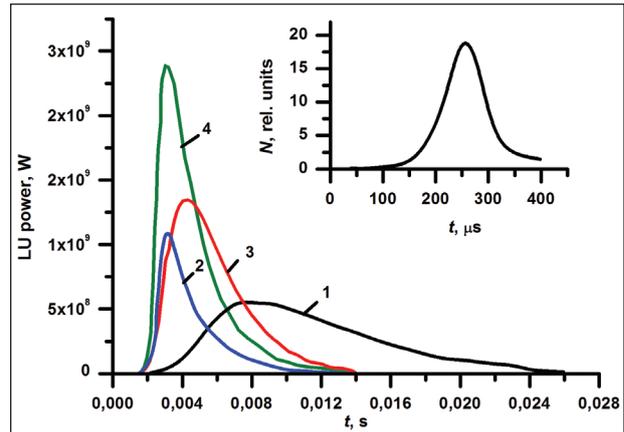
Polyethylene and paraffin are used as the materials of element of neutron moderator and reflector, respectively. The PMC represents aluminum tube standard for the LU design under discussion, filled with alternating fuel and neutron moderator pellets. Mass of fuel (uranium dioxide with  $^{235}U$  enrichment of 90%) in the PMC amounts to approximately 150 g; that of neutron moderator is equal to 3.5 kg.

OKUYaN is activated as follows. Laser unit is raised to the upper position using special lifting device. Reactor is moved from the shielding along the rails to be positioned under the laser unit occupying strictly fixed position. Laser unit is lowered into the lower position. As the result, the RCs appear to be positioned inside the LU. Reactor pulse is ignited by the command from control panel and measurements of required neutronics and laser characteristics of the facility are performed.

### 3. Neutronics characteristics of the OKUYaN

The purpose of investigation of OKUYaN neutronics characteristics essentially amounted to the search for such configuration of the LU and reactor operational mode when the direct  $RU \rightarrow LU$  coupling would be maximum, while the inverse  $LU \rightarrow RU$  coupling would be minimum. Three LU loading maps and two operational modes of the ignition reactors were investigated.

Results of studies are shown in Fig. 4. Pulse corresponding to the energy release in the reactor core for the case of reactor operation without the LU is presented in the cut-in. Pulses 1 – 3 correspond to the energy release in the LU (pumping pulse) when the reactor is operated in normal mode inside the LU with different loading maps, pulse n. 4 corresponds to the energy released in the LU in the case of modified reactor operation mode inside the LU.



**Figure 4.** Energy release pulses in the LU (Cut-in – energy release pulse in the reactor core during the operation outside the laser unit): 1, 2, 3 – loading maps n. 1, 2 and 3 for the normal reactor operation mode; 4 – loading map n. 3 for the modified reactor operation mode.

It is clear from the results presented in Fig. 4 that for all the investigated loading maps and for all reactor operation modes pulse duration in the laser unit significantly exceeds the pulse duration in the reactor core when the reactor is operated outside the LU. This is associated, in the first place, with the fact that the reactor works during pulse generation in the LU not on intrinsic prompt neutrons with lifetime of  $\sim 10$  ns, but, instead, on neutrons from three-zone coupled system lifetime of which is significantly longer (several microseconds (Dyachenko 2003)) and which represents, in this case, nothing else but an additional group of delayed neutrons.

Values of  $E_{LU} \sim 7$  MJ and  $\Delta t_{1/2}^{LU} \sim 2$  ms are evidently close to the limiting values of these variables in the case of use of Bars-6 reactor as the ignition reactor of the OKUYaN. It is clear that these values significantly differ from the values following from expressions (1) and (2). This is explained by high sensitivity of reactors of this type to neutrons pertaining to  $LU \rightarrow RU$  inverse coupling.

Based on the examined experimental data it is possible to suggest two methods for modernization of the ignition pulsed reactor for reducing the effects of  $LU \rightarrow RU$  inverse coupling and, consequently, for enhancing the OKUYaN energy characteristics (Dyachenko and Fokin 2012).

The first method refers to the reactor loaded with conventional fuel ( $^{235}U$ ,  $^{239}Pu$ ) and amounts to the development of fast enough (with time comparable with self-quenching) mechanism of forced transition of the RU to deep sub-criticality ( $\Delta k_{eff} \geq 3\beta_{eff}$ ) for the purpose of ensuring nuclear safe reactor excursion on prompt criticality exceeding the contribution of the LU in its reactivity. It is evident that this represents the task quite difficult from the technical viewpoint, and, probably, practical implementation of this task is even impossible.

The second, more cardinal, method is the application of threshold fissionable element, for instance,  $^{237}Np$ , as the ignition reactor fuel. Fission threshold amounts for this nuclide to about 0.25 MeV. Therefore, neutrons from

the LU with spectrum close to thermal spectrum entering the ignition reactor core will not initiate fissions of reactor fuel nuclei, i.e. the value of the inverse neutron coupling coefficient  $K_{inc}^{Np}$  in the case of fuel made of  $^{237}\text{Np}$  will be much less than the corresponding value of  $K_{inc}^U$  coefficient in the case of reactor core fuel made of  $^{235}\text{U}$ .

In order to estimate the coefficient let us use experimental data on the value of cadmium ratio in the laser unit. Its value averaged over the LU volume amounts to approximately 30 (Dyachenko 2003).

Maxwellian distribution of neutrons  $n(E)$  corresponding to such cadmium ratio is shown in Figure 5. Its temperature amounts to about 2850 K. Dependences of fission cross-sections of  $^{235}\text{U}$   $\sigma^U(E)$  and  $^{237}\text{Np}$   $\sigma^{Np}(E)$  are shown in the same figure. It can be demonstrated using the data presented in Fig. 4 that

$$K_{inc}^{Np}/K_{inc}^U = \left( \int_{1\text{eV}}^{\infty} n(E)\sigma^{Np}(E)dE \right) / \left( \int_{1\text{eV}}^{\infty} n(E)\sigma^U(E)dE \right) \approx 1 \cdot 10^{-5},$$

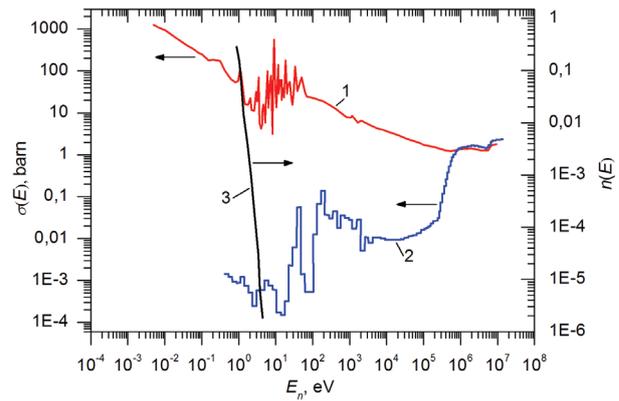
i.e. replacement of  $^{235}\text{U}$  with  $^{237}\text{Np}$  in the ignition pulsed reactor results in the decrease of  $\text{LU} \rightarrow \text{RU}$  inverse neutron coupling by about five orders of magnitude.

The question of use of  $^{237}\text{Np}$  as reactor fuel was discussed in (Seifritz and Wydler 1979, Konev 1981, Kolesov 1999, 2007, Shabalin et al. 2018). A whole series of publications, for instance (Konev 1981), are dedicated to the investigation of mechanical and thermal physics properties of neptunium and its alloys. The problem of  $^{237}\text{Np}$  use as fuel for the internal core (RC1) in two-section booster reactor with external core (RC2) loaded with  $^{235}\text{U}$  for creating super-powerful source of fast neutrons with the so-called gating neutron coupling between the reactor sections was examined in details in (Kolesov 1999, 2007).

The following two important conclusions can be drawn from the above discussion. Firstly, development of ignition reactor with fuel load consisting of  $^{237}\text{Np}$  appears, at last from the viewpoint of neutronics, to be a feasible task. Secondly, application of such ignition reactor in the OKUYaN would allow bringing energy balance of such reactor significantly closer to theoretical limit increasing, in particular, energy and power of the pumping pulse in the laser unit of the pilot sample of the OKUYaN by approximately 10 – 20 times.

#### 4. Laser characteristics of the OKUYaN pilot sample

Two gas mixtures He-Ar-Xe ( $\lambda = 1.73; 2.03 \mu\text{m}$ ) and He-N<sub>2</sub>-H<sub>2</sub> ( $\lambda = 0.391; 0.428 \mu\text{m}$ ) most thoroughly investigated by the respective time period and easiest from the viewpoint of technology (can be operated at room temperatures) were selected as LAEL laser-active media for demonstration of operability of the laser unit. The media in question were used in the studies of laser characteris-



**Figure 5.** Dependence of fission cross-sections  $\sigma(E)$  for  $^{235}\text{U}$  (1),  $^{237}\text{Np}$  (2) on neutron energy  $E_n$  and Maxwellian distribution of neutrons  $n(E)$  (3) for  $T = 2850 \text{ K}$ .

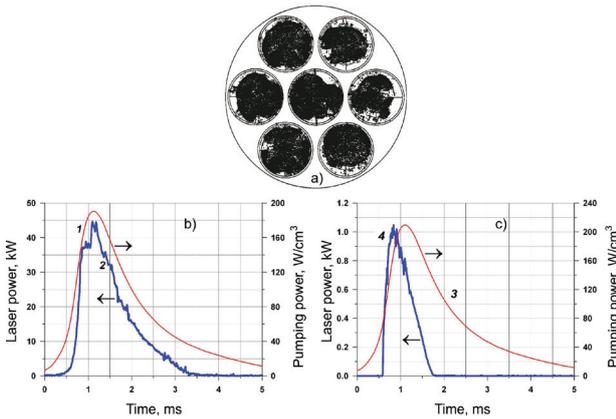
tics of the OKUYaN for different LU configurations and different laser and ignition reactor operation modes.

In particular, the mode of free generation on one LAEL in the composition of laser unit equipped with internal and external resonators was investigated. Free generation mode on seven LAEL, as well as modes of one- and two-pass amplifier on seven or 19 LAEL with uranium LAEL used as the driving generator operated in the free pumping mode and LAEL with volume pumping with  $^3\text{He}(n,p)^3\text{H}$  reaction products were investigated for He-Ar-Xe medium. Here, flat mirror was used in the two-pass mode instead of SBS cuvette, and Fresnel rhomb was used for rotating radiation polarization. Some of the obtained results are shown in Fig. 6. Laser beam “signature” obtained by burn method with target located in the radiating near-field zone demonstrates the possibility of extraction of laser energy from the multi-element system. Pumping pulses and laser generation pulses for the He-Ar-Xe medium ( $\lambda = 2.03 \mu\text{m}$ ) and He-N<sub>2</sub>-H<sub>2</sub> medium ( $\lambda = 0.398 \mu\text{m}$ ) presented in Fig. 6 characterize specific pumping and generation parameters for the media in question achieved using the test facility.

It is evident, for instance, that for He-Ar-Xe medium efficiency of conversion of energy of fission fragments imparted to the gas into laser radiation energy amounts to about 0.5 and to 1% for energy and power, respectively. This is approximately two times lower than the values following from the calculation kinetic model of this laser and values obtained on the first workplace of the test facility.

Studies (Dyachenko et al. 2015) of He-Ar-Xe-LAEL with different diameters and thicknesses of uranium coating demonstrated that scattering of laser radiation on gas density acoustic waves emerging because of strong radial non-uniformity of energy deposition in the LAEL active medium typical for fission fragments may be the cause of the observed discrepancy.

Studies for optimizing the LAEL design, selecting and investigating active media for specific practical applications of the installation were conducted on the first workplace of the “Stand B” test facility. Refs. (Denezhkin et al. 2015, 2019) on the investigation of characteristics LAEL on the basis of high-temperature Cd-He-steam-gas



**Figure 6.** Laser characteristics of the OKUYaN pilot facility: a) – laser beam “signature” at the output from the amplifier of the “Stand B” reactor-laser system ( $\lambda = 2.03 \mu\text{m}$ ); b) – pumping power (1) and total power along the whole laser generation channel ( $E_{\text{gen}} = 43 \pm 2 \text{ J}$ ;  $E_{\text{spec}} > 1.5 \text{ J/l}$ ) on the 2.03- $\mu\text{m}$  transition (2) in He-Ar-Xe medium; c) – pumping power (3) and total power along the whole laser generation channel (one LAEL;  $E_{\text{gen}} = 0.7 \pm 0.1 \text{ J}$ ) on the 391.4-nm transition (4) in He-N<sub>2</sub>-H<sub>2</sub> medium.

mixture (transition  $5s^{22}\text{D}_{5/2} - 5p^2\text{P}_{3/2}$  CdII,  $\lambda = 441.6 \text{ nm}$ ) which is of interest for space deployment of the OKUYaN and studies (Lapidus et al. 2003, Dyachenko et al. 2016) on the investigation of the possibility to use  $\text{POCl}_3 - \text{SnCl}_4 - {}^{235}\text{U}^{2+} - \text{Nd}^{3+}$  laser liquid (transition  ${}^4\text{F}_{3/2} - {}^4\text{I}_{11/2}$   $\text{Nd}^{3+}$ ,  $\lambda = 1.054 \mu\text{m}$ ) as the active medium of the land-based OKUYaN laser unit must be noted here.

It was demonstrated in (Denezhkin et al. 2015, 2019) that with minimization of losses of laser radiation in the LAEL due to scattering on gas, density waves emerging because of radial non-uniformity of energy deposition and use of isotopically pure cadmium ( ${}^{112}\text{Cd}$  or  ${}^{116}\text{Cd}$ ) laser efficiency at the level of 1.5% can be obtained on wavelength  $\lambda = 0.441 \mu\text{m}$  for lifetime of the upper laser level of about 0.5  $\mu\text{s}$ .

Interest in laser liquid is associated with the fact that because uranium is contained in the liquid in the form of solution, pumping efficiency for  $\text{Nd}^{3+}$  upper laser level (relative to the fission energy in the LAEL) is approximately 5 – 10 times higher as compared with gas laser and amounts, in accordance with experimental data (Lapidus et al. 2003), to ~2%. Beside the above, lifetime of  $\text{Nd}^{3+}$  upper laser level amounts to about 300  $\mu\text{s}$  which is comparable with duration of the pumping pulse. However, in contrast to gas lasers generation in the liquid with nuclear pumping has not yet been confirmed.

Transmission of laser beam with wavelength of 1.054  $\mu\text{m}$  for  $\text{POCl}_3 - \text{SnCl}_4 - {}^{235}\text{U}^{2+} - \text{Nd}^{3+}$  liquid in cuvettes with different aperture with excitation by uranium fission fragments was investigated in (Dyachenko et al. 2016) on the first workplace of “Stand B”. It was found that increase of aperture of the cuvette by 2.5 times results in the decrease of transmission of light by the liquid by four times. This is the most unexpected result from the viewpoint of existing understanding of penetration of light through the liquid. Similar to the case of gas laser the authors explain the above effect by the emergence of additional losses of laser radia-

tion in the medium during the pumping pulse due to scattering on hydroacoustic waves of liquid density developed due to the radial non-uniformity of energy deposition. However, the nature of this non-uniformity is different in this case and is associated with blocking of neutron flux by  ${}^{35}\text{Cl}$  isotope having high concentration in the liquid and relatively large thermal neutron capture cross-section equal to ~40 barn. The authors are of the opinion that it is specifically this effect, which is the main cause of failures in the attempt to obtain generation under nuclear pumping of uranium-containing liquid on the basis of aprotic acid. This effect can be significantly decreased or eliminated by replacing  ${}^{35}\text{Cl}$  isotope in the natural mixture with  ${}^{37}\text{Cl}$  radiation capture cross-section for which is smaller by 100 times.

## 5. Conclusion

1. Development and construction of pilot sample of optical quantum amplifier with nuclear pumping, investigation of neutronics characteristics of three-core reactor system and obtaining laser beam from the neutron-multiplying laser unit can be regarded as the proof of “theorem of existence” of reactor-laser system with direct conversion of nuclear energy into laser beam energy – the prototype of future facilities for nuclear-laser power engineering.
2. Experimental studies implemented on the “Stand B” test facility and performed theoretical studies of processes taking place in reactor-laser system allowed outlining the ways for further improvement of the system for the purpose of achieving the required level of energy characteristics of the laser beam.
3. It was established that in order to achieve the above goal it is necessary to solve, in the first place, the following two main problems.
  - The first problem pertains to the physics of multi-core reactors systems and is associated with high LU – RU inverse neutron coupling. It was demonstrated that this problem can be solved by replacing fuel composition in the ignition reactor ( ${}^{235}\text{U}$  isotope) with threshold  ${}^{237}\text{Np}$  fissionable isotope.
  - The second problem refers to laser physics and is associated with strong radial non-uniformity of energy deposition in the LAEL typical for nuclear pumping. Such non-uniformity results in the appearance of losses of laser radiation due to scattering on radial acoustic density waves in the medium. It was demonstrated that in the case of gaseous laser-active medium this problem can be solved by optimizing the LAEL design and in the case of uranium-containing laser liquid on the basis of aprotic acid it can be solved by replacing  ${}^{35}\text{Cl}$  isotope with  ${}^{37}\text{Cl}$ .

Solution of these problems will ensure achieving calculated parameters of reactor-laser systems and will allow initiating the development of full-scale pilot samples of optical quantum amplifier with nuclear pumping for practical implementation of the newest technologies.

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