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Portable Neutron Generator Based on Laser-Plasma Ion Diode with Magnetic Isolation

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The article presents a new experimental portable pulsed neutron generator based on a laser-plasma ion diode with magnetic insulation and the results of the first experiments. The laser-plasma diode makes it possible to obtain large ion current pulses that generate high-intensity neutron radiation. The source of optical radiation was a pulsed neodymium-doped yttrium aluminum garnet laser with a wavelength of 1064 nm, a pulse energy of up to 0.7 J, and a duration of ~ 10 ns. The ion beam is accelerated by an Arkadiev–Marx pulsed voltage generator with a voltage amplitude of up to 250 kV, a duration of up to $1.5\,\mu$s, and an energy of up to 160 J. Neutrons were generated using the reaction $d(d,n)\,^3$He. A neutron yield of $2 \cdot 10^6$ neutron/pulse was obtained.

Keywords: ion source, neutron pulse, pulsed voltage generator, YAG laser.

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Introduction

Portable pulsed neutron sources are used in many fundamental and applied studies. Generators based on vacuum neutron tubes (VNT) [1–3] and generators based on plasma focus (PF) chambers [4] are widely used among them. One of the main parameters of neutron pulses are neutron yield and duration, reach for VNT$\sim 10^6$ neutron/pulse per $d(d,n)\,^3$He reactions and $\sim 1\,\mu$s, respectively, and for portable (pulse energy ~ 10 kJ) of PF chambers — $\sim 10^{10}$ neutron/pulse per $d(d,n)^3$He reactions ~ 50 ns. Studies showed that portable pulsed neutron generators based on a laser-plasma ion diode with magnetic insulation can become a promising analogue of these devices [5,6]. The potential capabilities of such generators will make it possible to create sources with a neutron yield greater than that of VNT (up to 10^{10} neutron/pulse per $d(d,n)\,^3$He), with response frequency greater than that of the PF (up to 10 Hz), and high service life. Recent developments of portable pulsed neutron generators based on a laser-plasma ion diode with magnetic insulation achieved the neutron yield of $\sim 5 \cdot 10^7$ neutron/pulse ($d(d,n)\,^3$He) at an accelerating voltage of 280 kV, full width at half maximum $\sim 0.3\,\mu$s and laser pulse energy 0.1 J [6]. This paper is based on the experimental setup [6], differing significantly from it in the new system of magnetic isolation [7], and is a significant step towards achieving neutron yields of neutron generators based on laser-plasma ion diodes of about 10^{10} neutron/pulse per $d(d,n)\,^3$He reactions. The new magnetic system [7] is capable of providing both the electric strength of the accelerating gap and a satisfactory degree of back electron blocking as the laser pulse energy increases to values exceeding 0.1 J.

1. Experimental setup

The scheme of the experimental setup is shown in Fig. 1. Vacuum chamber *1* with volume ~ 15 l is made of stainless steel and contains the caprolon insulator with electrical strength up to 450 kV *2*. Through the high-voltage input in the insulator *2* and the peaking arrester *3*, the high voltage is supplied from the pulsed voltage generator (PVG) *4* to the anode with the laser target *5*. The system of magnetic isolation *6* with a conical neutron-forming target (cathode) *7* is installed near the laser target *5*. On the

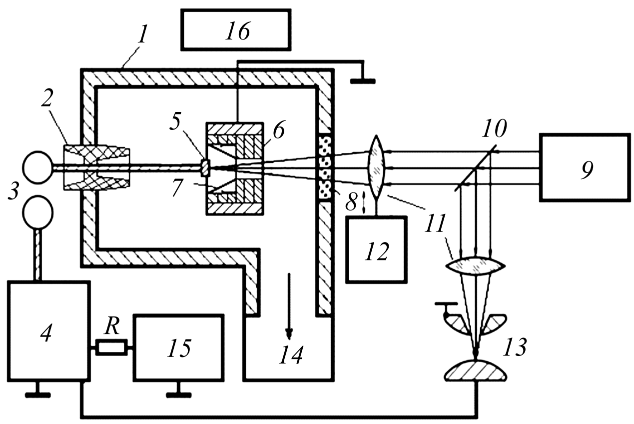

Figure 1. Scheme of the experimental setup: *1* — vacuum chamber, *2* — caprolon insulator, *3* — peaking arrester, *4* — pulse voltage generator, *5* — anode with laser target, *6* — magnetic isolation system, *7* — neutron-forming target (cathode), *8* — coated optical window, *9* — pulsed laser, *10* — plane-parallel transparent plate, *11* — coated lens, *12* — scanning device, *13* — laser controlled arrester, *14* — vacuum unit, *15* — high-voltage power supply unit, *16* — neutron yield meter.

opposite side of the chamber there is the optical window *8* with coating for the wavelength$\lambda = 1064$ nm, through which the Nd:YAG *9* laser radiation is introduced. The optical system consists of the plane-parallel transparent plate *10*, coated lens *11*, includes a scanning device *12* and, through the laser controlled arrester *13*, ensures start-up of PVG *4* and the formation of laser plasma on targets *3*. The vacuum chamber *1* is connected to the oil-free vacuum unit *14*, which provides low and high vacuum (up to 10^{-5} Torr) and has residual pressure monitoring sensors. PVG *4* is powered by the high-voltage power supply unit (up to +50 kV) *15*. The neutron radiation is registered by the neutron yield meter *16* TPIVN61 [8]. The residual pressure in the chamber during the experiments was at the level of $5 \cdot 10^{-5}$ Torr.

The magnetic isolation system *6* is an assembly of 6 cylindrical permanent magnets NMB 320/88 and NMB 310/130 [9] and a magnetic core made of steel 45. The magnitude of the modulus of magnetic field induction within five-millimeters from the surface of the conical neutron-forming target *7* is in the range 0.3–0.4 T, the degree of homogeneity $\sim 10\%$ is achieved over more than half of the target length. The detailed description of the development and design of this magnetic system is presented in [10]. Changes of the magnetic system with respect to its prototype from [6] are as follows: the length of the accelerating gap is increased by two times (from 15 to 30 mm) with an increase in the average value of the magnetic field induction modulus near the target surface from 0.31 to 0.36 T; the angle averaged over the length of the target between the vector of magnetic field induction and the target surface decreased from 26 to 15°; the fraction of the target surface in the half solid angle of spreading of the laser plasma increased from 0.84 to 0.97.

The neutron-forming target *8* is a cylinder made of duralumin with inner cone, on the surface of which 4 rows of 6 circles of compressed powder of deuterium-containing polyethylene with diameter of 8 mm are glued along the axis equidistant from each other. The neutron-forming surface thus occupies 10% of the target area.

A solid-state Nd:YAG laser *9* has the following characteristics: wavelength 1064 nm, pulse energy 0.2 or 0.7 J, pulse duration$\sim$ 10 ns, repetition rate up to 10 Hz, power density on the laser target $\sim 10^{10}$ W/cm^2. The radiation is focused by a short-focus quartz lens *11* onto the working surface of the laser target *5* made of ZrD with stoichiometry 0.8. The lens *11* is mounted on the scanning device *12*, which randomly changes the position of the focusing spot on the surface of the laser target, which increases its life.

The PVG is made according to the scheme of Arkadiev–Marx and consists of 10 cascades. In each cascade, KPIM3-50-0.05 capacitor is installed with a capacity of 0.05 μF and operating voltage up to 50 kV. Switching of capacitors is carried out by means of air uncontrolled arresters made of pairs of brass balls with an adjustable gap. The impact capacity of PVG is 5 nF, the amplitude of the output voltage is up to 350 kV, and the stored energy reaches 300 J. Self-inductance does not exceed 2 μH. To start PVG the laser arrester is used (with a switching delay with respect to the laser pulse 10 ns), whose breakdown is carried out by a part of the laser pulse ($\leq 10\%$) focused by the lens L2 and obtained by refraction of the main beam on the plane-parallel transparent plate P1. The delay time between the operation of the laser arrester R1 and the appearance of PVG voltage on the diode is about 70 ns.

The voltage on the diode under study is measured using a cascade of two voltage dividers. The first of them is made in the form of a shunt resistive divider, assembled on TVO-60 resistors with total resistance of 30 kΩ (with active resistance of the diode $\sim 100\,\Omega$) and having a division factor of 1:15.0. At its output Tektronix P6015A high-voltage divider with factor of 1:1000 is installed, which is connected directly to Tektronix TBS 1022 oscilloscope. The measurement error of both dividers is 2%.

The current is measured using a Rogowski coil installed in PVG discharge circuit between the vacuum chamber and the „ground" of setup, the coil has a conversion coefficient (56 ± 2) A/V in the range 10–2000 A (0.16–30.5 A/ns). Through a matching resistive divider 50 Ohm with a coefficient of 1:11.6, this coil is connected to the Tektronix TBS 1022 oscilloscope. The error of the Rogowski coil and the divider is 4%. The oscilloscope error for both measurements is 1%.

The neutron yield is determined by means of a neutron yield meter TPIVN61 [8]. It is designed to measure the neutron yield from the pulsed neutron emitter with neutron energy in the range 0.5–15 MeV with neutron pulse duration maximum 0.1 s. Its measurement range is $4.5 \cdot 10^5 - 0.8 \cdot 10^{12}$ neutron/pulse with a relative measurement error of the neutron yield maximum 20% and a confidence level equal to 0.95.

The pulse of neutron radiation in a laser-plasma ion diode with magnetic insulation is formed as follows. The beginning of generation is the start-up of the pulsed laser, whose radiation, when passing through the plane-parallel plate, is divided into two unequal beams. The main beam, carrying more than 90% of energy, passes through a focusing lens and is directed to the laser target consisting of a sorbent of hydrogen isotopes (usually Ti or Zn) and merely hydrogen isotopes. The second beam is deflected to the laser arrester, which is simultaneously the first arrester of VPG, and is focused on the surface of one of its electrodes, initiating the breakdown of the air gap and PVG start-up. Reaching the laser target, the main beam causes its ablation, ionization of the evaporated material and plasma heating, thereby forming a bunch of laser plasma expanding in an external magnetic field. Due to the complex geometry of the magnetic field inside the diode, different sections of the plasma bunch expand at different angles to the magnetic induction vector, but the plasma moves in the normal direction to the surface of the conical neutron-forming target predominantly across the magnetic field. The high voltage pulse appears on the laser target with some delay relative to the onset of plasma formation, due to the switching of all PVG arrester and the activation of the peaking arrester (for the setup described here — ~ 70 ns). Continuing the expansion, but already in the presence of an electric field, the laser plasma is a source of positively charged ions, both ions of the target material with charge up to $+14$, and hydrogen isotopes [11], which are accelerated to neutron-forming target. The small length of the accelerating gap (~ 30 mm) and the high accelerating voltage (~ 200 kV) do not allow the ions to be distributed in accordance with their charge-mass ratio [11], and the complex time dependence of the charge composition of the laser plasma makes it impossible to extract the current of hydrogen isotope ions in the total ion current without special studies. In this connection, the ion current extracted from the plasma can so far be considered only as the total current of target material ions and hydrogen isotopes with an unknown ratio. By supplying ions to the accelerating gap, the laser plasma expands until it either reaches the neutron-forming target or exhausts itself, which determines the duration of the ion current pulse. On a neutron-forming target the accelerated ions of both types initiate ion-electron emission, which delivers electrons to the accelerating gap, the electrons are accelerated back to the laser target and additionally load the PVG, and the magnetic isolation system counteracts to it. Thus, the total diode current consists of highly charged ions of the laser target material, hydrogen isotope ions, and some fraction of the back electron current. Hydrogen isotope ions on the target enter into the nuclear reaction with hydrogen isotopes adsorbed in it, generating neutrons.

2. Experimental results

The results of the experiments include oscillograms of the total current through the diode and the voltage across it (Figs. 2 and 3) obtained on a duralumin target (without deuterated polyethylene) at PVG amplitude voltage of 150 and 250 kV and laser pulse energy of 0.2 and 0.7 J. Section 2 also presents the results of neutron measurements at voltage of 200 kV and laser pulse energy of 0.7 J.

All oscillograms are obtained by averaging samples over 15 pulses that passed the frequency filtering below the level of 5 MHz (to reduce noise). The solid line in Figs 2 and 3 represents the processed pulse, and the dashed line shows the region of the confidence interval with confidence probability of 68% (one σ). The largest contribution to the confidence interval is made by the statistical scattering of pulses, which increased with increasing energy of both the PVG and the laser.

The detailed discussion of the experimental data will be given in Section 3. Now, let us review the primary importance of the results obtained only. The magnitude of the amplitude of the total current through the diode is for the considered parameters of PVG and the laser in the range $0.8-2.2$ kA with half-height duration of $0.2-1.0\,\mu$s. In the paper [6], which most of all served as a prototype of the current setup, the amplitude of the current pulses through the diode was ~ 120 A at the half-height duration of $\sim 0.3\,\mu$s, PVG amplitude voltage 280 kV and laser pulse energy 0.1 J. At the current setup, at PVG amplitude voltage of 250 kV and laser pulse energy of 0.2 J, the diode current with amplitude of 1.1 kA was obtained with half-height duration of $1.0\,\mu$s (Fig. 2). Thus, at a slightly lower voltage, but by a factor of two larger laser energy, the current pulse with nine times larger amplitude and three times larger duration was obtained. The reason for this is the only significantly changed part of the experimental setup — new system of magnetic isolation [7].

The neutron measurements were carried out at the PVG amplitude voltage 204 ± 10 kV and constituted a series of 10 pulses, whose neutron yield was recorded by TPIVN61. The resulting average yield was $(2.1 \pm 0.7) \cdot 10^6$ neutron/pulse. Taking into account the fact that only 10% of the target area was covered with neutron-forming deuterated polyethylene, the total neutron yield shall be $(2.1 \pm 0.7) \cdot 10^7$ neutron/pulse. In the paper [6], PVG amplitude voltage 200 kV corresponded to the neutron yield $5 \cdot 10^6$ neutron/pulse, which was achieved at a two times lower laser energy, but with the laser target stoichiometry of 1.6 (in contrast to 0.8 in the current experiment). Thus, the neutron yield of the new laser-plasma ion diode increased only by 4 times in comparison with its predecessor from [6], which is much less than the increase in the amplitude and width of the pulse of the diode current. The reasons for this will be discussed in the next Section.

3. Discussion of results

The zero time mark on the oscillograms in Figs 2 and 3 corresponds to the time of the laser arrester P1 activation, as well as the beginning of the laser plasma expansion and PVG start-up. According to the literature data [12–15], the average rate of laser plasma expansion in the gas-dynamic mode at the laser radiation wavelength of 1064 nm, a power density $\sim 10^{10}$ W/cm^2, and pulse duration 10 ns is $\sim 10^7$ cm/s or 10 cm/μs. The length of the accelerating gap is ~ 30 mm, so, in the magnetic field absence the plasma shall bridge it for the time $\sim 0.3\,\mu$s. Here, the end of the voltage pulse across the diode is observed at time moment in the range $1-2\,\mu$s after the laser plasma appearance. Thus, the magnetic field action decelerating the plasma is observed.

Meanwhile, to obtain a high neutron yield on the laser-plasma diode, not only the high value of the deuterium ion current is of great importance, but also the duration of this current, they together will give a greater neutron yield per pulse. The magnetic field in plasma ion diodes is considered mainly as a mean of suppressing back electrons, and for metal neutron-forming targets it can increase the energy efficiency (number of neutrons per unit of energy) of the diode by maximum 3 times [16] relative to the diode without the field, when for each ion accelerated to the

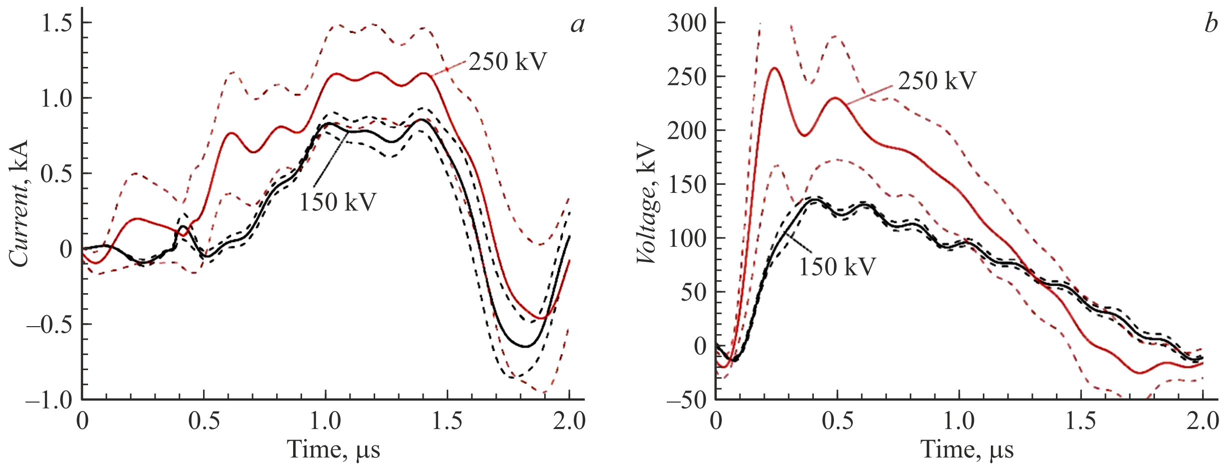

Figure 2. Oscillograms of current (a) and voltage (b) on diode — solid line, confidence interval equal to one σ — dashed line, at PVG amplitude voltages of 150 and 250 kV and laser pulse energy of 0.2 J.

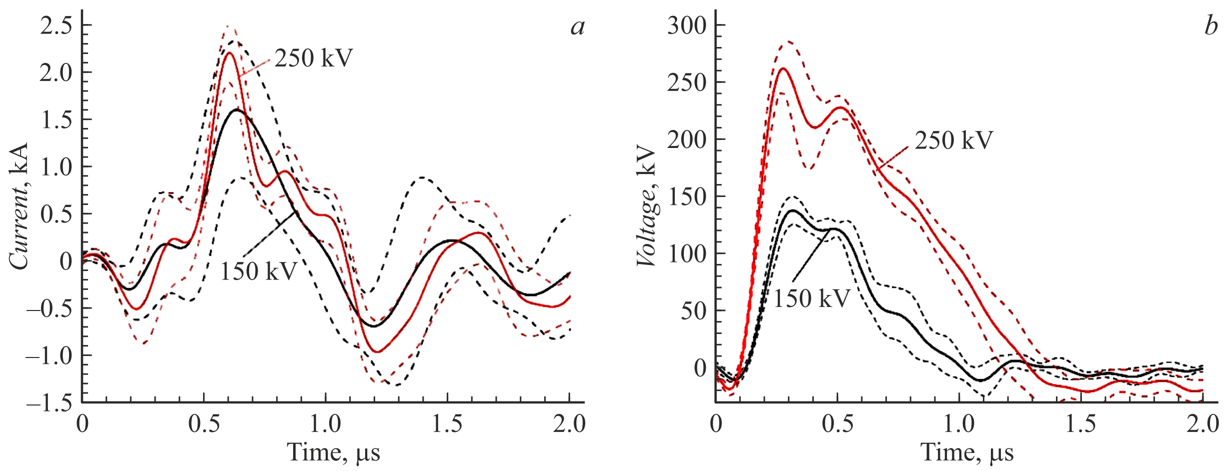

Figure 3. Oscillograms of current (a) and voltage (b) on diode — solid line, confidence interval equal to one σ — dashed line, at PVG amplitude voltages of 150 and 250 kV and laser pulse energy of 0.7 J.

target, there will be 2 back electrons. With a constant PVG and sufficient laser energy, this means that the neutron yield can be increased by three times while ensuring complete suppression of the back electrons. The data in Fig. 2 demonstrate a six time increase in the pulse width of the diode current, moreover, as compared with the option with magnetic field, but with a less successful configuration [6]. Thus, the magnetic field as a laser plasma decelerator has a much greater positive effect on increasing the neutron yield in the laser-plasma ion diode than as a mean blocking the back electrons near the target surface. Besides, the increase in the neutron yield by the laser plasma deceleration has a great potential, ultimately limited only by the laser pulse energy (up to 10 J in portable serial lasers) and the technical means creating the magnetic field (up to several T in pulsed magnetic systems). while complete magnetic isolation of all electrons cannot lead to more than by three times increase in the neutron yield.

The value of the charge transferred per pulse increases with the increase in the PVG amplitude voltage at both laser pulse energies used (Fig. 2 and 3). It follows that the diode operates in the mode of current limitation by the space charge. According to Child–Langmuir law, the diode current shall increase monotonically due to the laser plasma expansion and the corresponding shortening of the accelerating gap. The current „plateau" observed in Fig. 2 shall be explained by the diode voltage decreasing along the pulse (Fig. 2, b), which compensates for the gap shortening between the plasma and the cathode. The length estimation of this gap Δr using the Child-Langmuir law for the cylindrical diode and average particle with charge-mass ratio of $e/m = 11 \cdot 10^6$ C/kg [11] (D^+: $e/m = 48 \cdot 10^6$ C/kg, Zr^{+1}: $e/m = 1.1 \cdot 10^6$ C/kg, Zr^{+13}: $e/m = 14 \cdot 10^6$ C/kg) gives for $1.0\,\mu s$ $\Delta r_{1.0} \approx 3$ mm, and for $1.5\,\mu s$ — $\Delta r_{1.5} \approx 2$ mm (Fig. 2, a). Here the velocity of the decelerated plasma boundary is $\sim 0.2\,cm/\mu s$, which, in any case, is less than the expansion velocity of the laser plasma undisturbed by the magnetic field, which is $\sim 10\,\mathrm{cm}/\mu\mathrm{s}$ [12–15]. For the case 0.7 J „plateau“ is not observed, which will be explained below, but a similar estimate Δr for the peak current gives the same 3 mm. Meanwhile we can conclude that laser plasma is capable of provide to the accelerating gap ($r_{\mathrm{acc}} \sim 30\,\mathrm{mm}$) ions in the amount necessary for generating a significant amount of neutrons only when the plasma directly approaches the neutron-forming target ($\Delta r / r_{\mathrm{acc}} \sim 10\%$). Thus, a long accelerating gap is necessary only to ensure its electrical strength throughout the entire high-voltage pulse, and currents equal to kiloampere are possible only when the laser plasma approaches the cathode. In this connection, the magnetic field shall be concentrated as strongly as possible near its surface to decelerate the laser plasma expansion to a lesser extent during its „idle“ movement towards the target.

Comparison of the current and voltage oscillograms in Figs. 2 and 3 shows that the voltage applied to the accelerating gap is equal to its amplitude value only when the diode current does not exceed ~ 100 A. When it is exceeded, the voltage begins to decrease linearly until it reaches zero. The energy stored in PVG for pulse with amplitude of 150 kV is 60 J, and for pulse with 250 kV — 160 J. The same energy values are obtained when calculating the energy released in the diode on the basis of the oscillograms in Figs. 2 and 3 — 60 J for case 150 kV and 160 J for the case 250 kV, at that similarly for both energies of the laser pulse. Thus, the PVG does not have enough stored energy to maintain the amplitude value of the accelerating voltage at kiloampere current load, and the voltage drops immediately after the noticeable current appearance.

The peak shape of current pulses at 0.7 J of energy in the laser pulse is now explained as follows. The higher laser energy generates a faster expanding laser plasma (including in the magnetic field), which results in the faster increase in the diode current. But the higher current causes higher energy consumption, as a result of which the accelerating voltage decreases faster: at 150–30 kV — for $0.5\,\mu$s for 0.2 J, at 120 kV — for $0.5\,\mu$s for 0.7 J, at 250–70 kV — for $0.5\,\mu$s for 0.2 J, and at 140 kV — for $0.5\,\mu$s for 0.7 J, resulting that the limiting diode current sharply decreases after reaching significant values, which gives the observed peak.

The lack of PVG energy is also the reason for the smaller increase in the neutron yield (by 4 times relative to [6]) in comparison with the increase in the amplitude and width of the current pulse (by 9.3 times relative to [6]). So, at the amplitude voltage on the diode of 150 kV the average value of the voltage per current pulse is 60 kV only, and for 250 kV — 110 kV. Neutron carried out at the voltage amplitude of 200 kV correspond to average voltage of 90 kV. Using the data on the nuclear reaction cross-section $d(d,n)\,^3$He [17], it is possible to estimate the neutron yield that shall be obtained on available laser-plasma diode current pulses under stepwise accelerating voltage pulse of amplitude — $(9 \pm 3) \cdot 10^7$ neutron/pulse. This estimate takes into account only the increase in the neutron yield associated with the increase in the deutron energy, but does not take into account the increase in the deutron current itself with the increase in voltage, and therefore the final neutron yield shall be higher.

The team of authors currently develops and manufactures PVG with voltage 300 kV and energy of 1200 J. The neutron yield of the laser-plasma diode presented here with this PVG shall increase to 10^9 neutron/pulse per $d(d,n)\,^3$He of the reaction.

Conclusion

Experiments were carried out on the generation of neutrons in new portable pulsed laser-plasma ion diode with magnetic isolation of secondary electrons by the field of permanent magnets. The diode current pulse parameters were in the following ranges: amplitude 0.8–2.2 kA, width $0.2-1.0\,\mu$s at accelerating voltage amplitude up to 250 kV and laser energy up to 0.7 J. At the same time, the energy stored in the Arkadiev–Marx PVG was not enough to maintain the amplitude value of the voltage throughout the entire current pulse. The neutron yield of $(2.1 \pm 0.7) \cdot 10^6$ neutron/pulse was achieved on the incomplete target, occupying only 10% of the possible area, at an accelerating voltage amplitude of 200 kV (110 kV on average) and laser energy of 0.7 J. The neutron yield, which shall be obtained at stable voltage of 200 kV across the diode (sufficient energy content of PVG) and full target, was estimated below as $(9 \pm 3) \cdot 10^7$ neutron/pulse. The analysis of the oscillograms of the diode current and voltage showed the significance of the action of the magnetic field decelerating the laser plasma expansion on the final value of the neutron yield. It manifests itself in the increase in the pulse width of the diode current, as well as increase in the current amplitude to kiloampere values, which is possible only when the plasma is located near the target surface (< 3 mm, which is 10% of the total length of the accelerating gap) for a long time.

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Conflict of interest

The authors declare that they have no conflict of interest.

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