Small-size high-current ion diode with pulsed magnetic insulation of electrons for 500 keV energy

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Abstract. The work informs about the development of an experimental model of light ion and deuteron accelerator with energy up to 500 keV at a current of approximately 1 kA. The current density of 20 A/cm$^2$ is reached in pulses with duration of less than 0.5 $\mu$s at a repetition rate of 1 Hz. The accelerator applies the magnetic electron insulation technique in the accelerating gap. In addition, an intense laser-plasma ion source is used. The diode features and operation modes are considered using the conical geometry of a spiral line forming the magnetic field.

1. Introduction

Investigations of small-size vacuum laser-plasma diodes, which have been performed in recent years for the purpose of creation of a compact impulse neutron generator [1–3], showed the possibility of effective deuteron acceleration to implement a nuclear reaction $D(d,n)^3$He in a diode with a laser deuterium-containing target on the anode and magnetic insulation of the electron current.

Such diode system has a coaxial geometry of electrons with the inner anode being covered by a hollow cylindrical cathode. The diode accelerates the deuterons arising from an anode target in the direction of the cathode target which is a source on neutrons. In these experiments, the application of a pulsed Nd:YAG laser (neodymium-doped yttrium aluminum garnet), wavelength of $\lambda = 1.06 \mu$m, radiation energy up to $W \approx 0.1$ J, duration of $\sim 10$ ns) and a pulsed high-voltage source with an accelerating voltage of $U_{\text{acc}} \approx 300$ kV, which is made via the Arkadyev–Marx scheme, allowed to produce accelerated deuteron flows with a current of up to 100–150 A [1].

The planning of experiments, which are intended for the augmentation of accelerating voltage up to 500 kV and laser radiation pulse energy up to 1 J, as well as the development and optimization of the diode gap magnetic insulation system, while accounting for the transfer to higher voltages and laser radiation energies, became the natural work progression [3, 4].

The fundamental changes, as compared with previous experiments on the deuteron acceleration in a vacuum diode with laser plasma on the anode, are related to the application of a high-power laser. Another fundamental difference consists in the use of a high-power Arkadyev–Marx generator with the designed shock voltage up to 500 kV. Moreover, the pulsed magnetic insulation is applied in the test experiments instead of the suppression of electronic conductivity by the constant magnetic field.
2. Investigation of accelerating ion triode with magnetic insulation

2.1. Experimental determination of the optimal parameters of laser spark sources of deuterons
The deuteron source, which is used in the accelerating diode for neutron generation, is one of the most important elements of pulsed neutron generator because it mainly defines the threshold characteristics of neutron pulse. In the case of vacuum diode, it can be made based on either vacuum-arc discharge plasma or laser plasma.

Vacuum-arc deuteron source operates most effectively within the microsecond range when the deuteron flight time in diode gap is considerably lower than the accelerating voltage pulse duration. Thereby, a deuteron bunch is formed and accelerated in compliance with the Boguslavskiy–Child–Langmuir model [5]. The model analysis showed that the emission current of deuteron source has a considerable effect on the process of deuteron extraction from plasma. A partial diode locking by a space charge already occurs at the current of ~10 A and a pulse duration of tens of nanoseconds. Besides, the neutron yield and neutron pulse duration are considerably reduced with the growth of emission current from the cathode [6].

Experimental investigations using prototypes showed that the application of spark laser deuteron source, which ensures quick deuteron extraction from plasma, was more effective in the nanosecond range of neutron pulses durations. The use of deuterium plasma, which is created on the anode when the laser is focused on the metal deuteride target, is its distinctive feature.

2.2. Choice of the optimal magnetic field
Different suppression methods of secondary electron emission from cathode, including schemes with magnetic electron insulation in the accelerating diode gap, are used in pulsed ion diodes to increase the energy efficiency of neutron generation.

The application of magnetic insulation in small-size coaxial systems, which are intended for deuteron acceleration and neutron generation, is primarily described in [7]. The electron conduction suppression by the permanent magnet field with the azimuthal symmetry was investigated in [1, 3]. The applications of pulsed magnetic field of spiral line with a current inside the cathode were investigated in [3, 8]. In this case, the critical magnetic field induction in the cathode region of accelerating gap is in the range from 0.2 to 0.6 T for the cathode diameters of 5–10 cm and accelerating voltages of \( U = 100–500 \) kV. The experiments show that the electron conduction suppression by the permanent magnet field [1] suffers from grave shortcomings, which occur due to the complex configuration and nonuniformity of the permanent magnet field. This results in the impossibility of axial magnetic field creation with the induction of no less than 0.4 T in the entire space between the cathode and laser plasma front (i.e., plasma anode), which is required for the complete suppression of electron diode conduction at the laser energy of \( W > 0.1 \) J.

The considered shortcomings manifest themselves to a lesser degree in diodes with the pulsed magnetic insulation. A strong magnetic field is created in the vicinity of the cathode during the current flow via a spiral induction coil, which is located inside. Its generatrix repeats the shape of hollow cathode, which can be made either in the form of a cylinder or a truncated cone. For such geometry, one should take into account that, in the pulsed mode with a high rate of current rise, the inductive current will also affect the process of magnetic field formation by induction coil.

2.3. Schematic of the experiment
The schematic of the experiment is specified in Fig. 1. The insulating magnetic field was generated by the positive-going current pulse. The current generator is made according to the scheme in which a capacitive storage \( C_M = 0.25 \) µF is discharged through a spiral coil with an inductance of \( L_M = 0.65 \) µH. The energy of 25 – 40 J is accumulated in the capacitive storage.
The characteristic current rise time (i.e., magnetic field) was $\tau_m \approx 400$ ns. A laser switch (LS), which also simultaneously switched the capacity in the first section of the Marx high-voltage pulse generator (HVPG), was applied for switching the storage capacitor $C_M$. Such scheme ensured the reliable current pulse synchronization (magnetic field generation) with the accelerating voltage pulse. The start of the current pulse coincides with the LS breakdown. Let us note that in these experiments with laser plasma, which are directed at the diode current recording, three processes are synchronized: laser plasma expansion, accelerating voltage formation and generation of the increasing magnetic field. The maximum current that is reached in the inductance coil can be estimated from the energy balance. It is equal to $I_{\text{max}} \approx 9$ kA. For this current, the magnetic field at the axis of conical spiral coil is $B_{\text{max}} \approx 0.5$–0.6 T. Moreover, already after a quarter of period from the beginning of current rise, the magnetic field is $B \approx 0.7 B_{\text{max}}$. The estimate of the efficiency of magnetic field generation showed that after 300 ns from the start of laser plasma expansion, the current in the conical coil equals to 60% of its peak value.

The circuit consisting of an inductor $L = 400$–700 $\mu$H and a compensating capacitor $C \approx 30$ pF (time constant $\approx 110$–150 ns), as well as a spark gap $G_2$, are added to the electric scheme to coordinate the accelerating voltage between the output of the Marx generator and the diode load with the processes of acceleration in the diode gap and the increasing magnetic field. In this case, the total delay of voltage pulse relative to laser pulse equals to $\tau_{\text{ delay}} \approx 200$ ns. Inductor is a 20-turn cylindrical spiral, where a ferrite core, M400HH, (70-mm diameter, 500-mm length) is inserted. The spark gap $G_1$ separates the LC circuit from the charging voltage of the Marx generator.

A Nd:YAG laser, which generates a radiation pulses with the wavelength of 1.06 $\mu$m, energy $\leq 0.85$ J and duration $\approx 10$ ns in the high-Q resonator mode, was used to obtain laser plasma. The current in the experiment was measured by the Rogowsky coils.

Under our experimental conditions, the upper limit of accelerating voltage was determined only by the maximum voltage that is generated by the Marx generator. In the absence of laser radiation on the anode, the vacuum gap breakdown did not progress. If the laser plasma was present on the anode, the initial stage of the discharge rapidly turns into the high-current spark stage, which was stipulated by the development of electronic current and conductivity rise in the gap between the plasma anode and
cathode. In turn, this led to the reduction of accelerating voltage. However, the application of pulsed insulating magnetic field allowed a considerable suppression of electron current. Moreover, the current in the spiral coil, which was equal to ~5 kA, prevented the breakdown between the cathode and anode during the first 0.5 µs from the initiation of laser pulse. The current of up to 1 kA at the ultimate accelerating voltage of up to 400 kV was recorded in the triode with magnetic insulation at the radiation energy on the laser target of 0.75 J.

The abovementioned information is required for the theoretical estimate of possible neutron yield in the considered diode system. The neutron yield per pulse can be determined using the following equation:

\[ Q(W) \approx \frac{n}{e} \int_0^\tau dE \int_0^{u(t)} dF(E) \frac{\sigma(E)}{F(E)}, \]

where \( n \) is the concentration of reagent nuclei in the neutron forming target, \( e \) is the elementary electric charge, \( \tau \) is the pulse duration of the deuteron current, \( U(t) \) is the time dependence of the accelerating voltage, \( F(E) \) is the deuteron energy loss per unit of target length, and \( \sigma(E) \) is the micro-section of the nuclear reaction.

3. Conclusions
The current of approximately 1 kA at the ultimate accelerating voltage up to 500 kV was achieved at the laser radiation energy on the target of 0.75 J in the diode with magnetic insulation. The current in spiral coil, which was equal to 5 kA, prevented the breakdown between the cathode and anode during the first 0.5 µs.

Calculations of the optimal apex angle \( \alpha \) of the conical cathode and spiral coil near the cathode gave the value \( \tan(\alpha) \leq 0.5 \). Moreover, at this angle, the deuteron yield from the anode plasma is maximal.

The application of pulsed magnetic insulation using the magnetic field generated by a spiral coil with the current flowing through it showed the complete absence of breakdowns between triode electrodes. This scheme has advantages as compared to the permanent magnet system, although it is less compact than the latter.

The optimal magnetic field induction in the gap between the plasma anode and cathode with a pulsed solenoid coil was found to be in the range from 0.5 to 0.8 T.

At the optimal magnetic field, the designed accelerating ion triode makes it possible to create deuteron bunches with energy of approximately 500 keV with currents of approximately 1 kA in the systems with the size of less than 10 cm.

Calculations that are based on experimental data on the obtained bunches of accelerated light ions, show that the neutron yield of nuclear reaction of \( \text{T}(d,n)^{3}\text{He} \) can reach \( 10^{11} \) neutr./pulse.

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