HYDROGEN NUCLIDES ACCELERATION FROM LASER PLASMA IN THE DIODE WITH MAGNETIC INSULATION OF ELECTRONS

K.I. Kozlowski, E.D. Vovchenko, V. L. Shatokhin, A.E. Shikanov, National Research Nuclear University "MEPhI" (Moscow Engineering Physics Institute), Moscow, Russia

Abstract

The results of an experimental investigation of the deuterons acceleration from laser plasma in a compact magnetically insulated ion diode are reported. The experiments were done in a pulsed mode ($U \leq 300$ kV, $I_{max} \leq 600$ A, $\tau \leq 500$ ns) at a pressure of 0,01 Pa. The deuterium laser plasma was produced at the anode during irradiation of a TiD target with a laser pulse (wavelength $\lambda = 1060$ nm and intensity $q \sim 5 \cdot 10^{14}$ W/m^2). The positive accelerating voltage was created by means of a 20 stage Marx generators with air spark gap-switched circuit. The ion diode has an axially symmetric geometry of the anode-cathode gap. A hollow cylindrical cathode made of a permanent magnet with induction on an axis up to 0,4 T. Magnetic insulation of electrons in the accelerating gap leads to suppression of the electronic components of the total current in 4-5 times.

INTRODUCTION

Plasma diodes are widely used for producing intense beams of electrons and ions with currents up to 100 kA and energy 100÷500 keV. Such high-energy dense beams of charged particles are applied in various fields of science and technology (for example, in ion implantation materials, injection of charged particle accelerator, neutron and x-ray radiation). In this work we discuss only the ion diodes developed for the generation of neutron radiation.

Currently, new technologies are being developed on the basis of compact pulsed neutron generator (PNG), such as screening and detection of dangerous substances and items, neutron logging oil and mineral deposits, neutron activation analysis [1]. Much attention in this research is given to the hydrogen nuclides acceleration on the basis of vacuum and gas-filled pulse diode and the optimization of their design, aimed at increasing resource and neutron yield. In this case work with the sealed designs on tritium gives an increase in the neutron yield by two orders of magnitude, however due to of high radiation danger their application is extremely limited. The main part of basic researches is carried out on a deuterium.

Good prospects for the development of compact PNG provides the use of the diode with magnetic insulation of the electrons and the laser-plasma source of deuterons [2, 3]. In environments with strong magnetic fields, the electrons move along the trajectories of the cycloid, not already captured the anode plasma and does not overlap the accelerating gap. According to preliminary estimates in such laser-plasma diode can be achieved density of the ion current up to 10^6 A/m^2. Such scheme has high efficiency for radial extraction of deuterium ions from the side surface of a laser-induced plasma cloud and provides higher emission characteristics compared to the vacuum-arc ion sources. It is simple and convenient to install the laser target on the high-voltage electrode. In addition, the laser-plasma diode allows to vary the initial parameters of the plasma by changing the intensity of the laser radiation.

Neutron generators on the basis of laser deuterons sources began to be developed for a long time, about 30-40 years ago [4, 5] (in MEPhI, JINR (Dubna), All-Union Scientific Research Institute of Nuclear Geophysics and Geochemistry, some other research centers). However, these experimental studies have significantly limited the absence of laser technology with high performance. At the same time had no active development of the idea of magnetic insulation of electrons. The main part of neutron generators based on the laser-plasma diode with magnetic insulation of electrons remained as experimental models. Now, this work is continued in National Research Nuclear University MEPhI again, due to the possibility of using compact new lasers and new super-strong permanent magnets.

THE EXPERIMENTAL SET-UP

Experimental investigations carried out on the model of laser-plasma diode with direct acceleration of deuterium ions from anode laser plasma to the cathode-target, forming neutrons (DD reaction). The diode has an axially symmetric geometry of electrodes (Fig. 1) with the internal high-voltage anode and the external hollow cylindrical cathode. At the anode is installed laser TiD target. Electrodes are established in the vacuum chamber equipped with means of pumping for obtaining residual pressure to $5 \cdot 10^{-2}$ Pa. For connection of the high voltage anode with Marx generator is used the vacuum electrical connector. It isolator is designed for an operating voltage up to 500 kV.

In the diode, for the purpose of increase in ion acceleration effectiveness, the scheme with magnetic insulation of electrons is applied. The magnetic field is created by the permanent magnet which is at the same time the cathode of the diode. The cathode has a form of the hollow cylinder with an internal radius of 0,02 m and 0,06 m high. The required induction value B was estimated from a comparison of the Larmor radius r_L of accelerated electrons with the distance between the plasma anode and cathode. From a condition of

$$r_L = [(2mU)/(eB^2)]^{1/2} < 5 \cdot 10^{-3} \text{ m}, \qquad (1)$$

where $U = 300$ kV − the accelerating voltage, m and e – the mass and elementary charge of electron, follows $B \approx$

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0,4 T. Realization of a stationary magnetic field with such induction value is possible, for example, at a choice of a magnetic material based on of NdFeB.

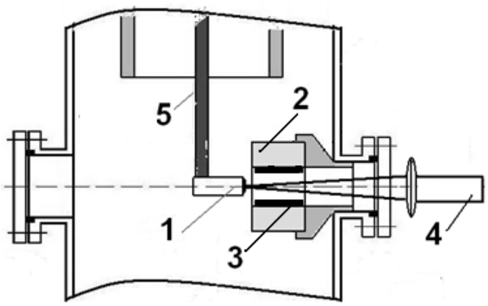

Figure 1: Laser-plasma diode. 1 − the anode with a laser TiD target; 2 – the hollow cylindrical cathode (NdFeB); 3 – place target, forming neutrons (DD reaction); 4 − laser radiation; 5 – vacuum electrical connector

A compact YAG laser with a wavelength $\lambda = 1060$ nm was used for produce of laser plasma. It has energy of 0,1 J and the duration of the laser pulse of 7 ns in giant pulse formation mode. These characteristics correspond to intensity $q \sim 5\cdot10^{14}$ W/m^2. The laser pulse was detected using the photocell (FEC−09) and a digital oscilloscope. Amplitude of the accelerating voltage was determined by means of a sphere spark gap and the table of breakdown voltages [6]. High-voltage divider was used for monitoring of temporary characteristics of pulse voltage.

Discharge current was measured by Rogovsky coil which was developed for work in the conditions of an intensive electromagnetic disturbance. Rogovsky coil has sensitivity 10 A/V in a mode of a current transformer.

The pulse Marx generator of high voltage was applied in experiments. It consists of a 20 step-section with air spark gap-switched circuit. The energy about 0,5 J was accumulated at a charge voltage of 15 kV in each from 20 step-section. The output voltage has amplitude up to $U = 300$ kV without loading ($R_H = \infty$), front duration less than 100 ns and the time constant τ_{RC} = 75 μs. At connection as loading of a laser plasma diode three different modes of its work were experimentally investigated.

EXPERIMENTS AND ANALYSIS

Mode 1 − testing of the diode system without laser radiation. Researchers showed that without of laser plasma the high-current discharge does not develop. In this case Marx generator works only for very large loading, and its output voltage practically is not distorted. The slight decrease in amplitude to 0,9U is observed in experiments. It can be explained as formation in the vacuum volume of the low-current discharge due to ionization of residual gas in the conditions of enough strong electric (≈ 20 MV/m) and magnetic (≈ 0,3 MA/m) fields. In the conditions of higher vacuum these ionization processes probably can no considered.

Mode 2 − main accelerator mode in laser-plasma diode with magnetic insulation of electrons. It is the mode high-current discharge and it is observed only with formation of laser plasma on anode. Waveforms of accelerating voltage and the discharge current are shown in Fig.2. They show that the Marx generator has a mode of aperiodic discharge capacity on the plasma load. In this case, resistance of the plasma R_p is limited from below by the value of the critical resistance of discharge circuit $R_c = (L/C)^{1/2} = 300\ \Omega < R_p$, where $C = 230\cdot10^{-12}$ F, $L = T^2/(4\pi^2 C) = 5$ μH, and the oscillation period $T = 2\pi\cdot(LC)^{1/2} = 220$ ns was determined from experience in the short circuit in the Marx generator.

On the other hand for high current discharge the resistance of plasma should not be large. The resistance of the plasma R_p is limited from above by the value $R_{max} = kU/I$, where discharge current I was determined from experience (see Fig. 2b) and the factor k takes into account that the voltage U decreases as the capacity is discharged. Because the duration of the discharge current is much smaller than the time constant τ_{RC}, the capacity does not have time to discharge. This is confirmed experimentally, since the amplitude of the accelerating voltage decreases only to a value 0,8U ($k = 0{,}8$). Maximum discharge current has been measured by the Rogowski coil and amounted to the value $I = 150$ A. Then $R_p < R_{max} = 0{,}8U/I \approx 1600\ \Omega$ and the resistance of the plasma can be estimated by the average $R_p = (R_c + R_{max})/2 \approx 1$ kΩ.

For aperiodic discharge capacity C in a circuit containing inductance L and resistance R_p, the temporal behavior of the current is described by the expression

$$i(t) = (U/L)\cdot(p_1 - p_2)^{-1}[exp(p_1 t) - exp(p_2 t)], \qquad (2)$$

where p_1 and p_2 – roots of the characteristic equation corresponding to this process. Effect of a non-linear dependence of R_p from the current $i(t)$, the calculation of transient processes is quite complicated. However for the limiting case when roots of p_1 and p_2 are real and equal each other (i.e. when $R_p = R_c$) expression for current becomes simpler

$$i(t) = -(U/L)\cdot t\cdot exp(-t/t_p), \qquad (3)$$

where $t_p = 2L/Rc = 30$ ns − the time to reach the current of the maximum values. Then the maximal value of calculated current $i_p \approx (U/L)\cdot(t_p/e) \approx 670$ A. Comparison of values $i_p \approx 670$ A and $I \approx 150$ A and estimation $300 < R_p \approx 1000 < 1600\ \Omega$ qualitatively confirm the correctness of the current measurement.

To synchronize the pulse of acceleration voltage with the process of moving laser plasma was used "optical" scheme. 25% of the total laser energy is gone in the first spark gap of Marx generator, causing its breakdown and switching in other sections. In this case the delay of the pulse voltage relative to the laser pulse, as a rule, did not exceed 100÷200 ns.

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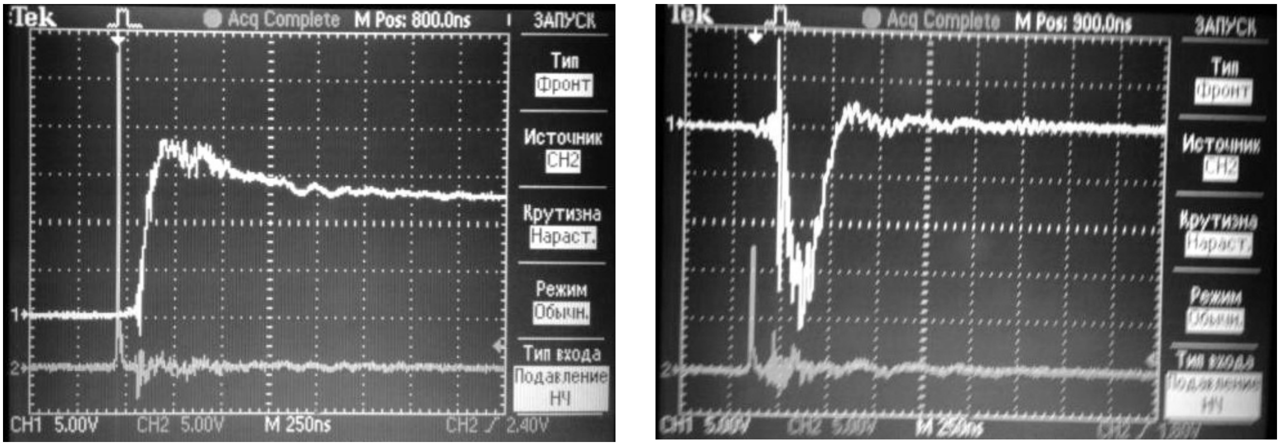

a) the accelerating voltage (the top beam) and a laser pulse (the lower beam)

b) discharge current (top beam) and laser pulse (lower beam)

Figure 2: Marx generator in mode 2 (sweep speed −250 ns /div)

Mode 3 − monitoring of effectiveness of magnetic insulation of electrons. In this mode of diode operation also the laser initiation was carried out, but without magnetic field. Instead of the cathode of the permanent magnet was mounted non-magnetic Al cathode with the same dimensions. The total current of the diode with the non-magnetic cathode is increased to 600 A in comparison with the mode 2, and amplitude of the accelerating voltage is decreased to 0,5U. It means that without magnetic field the current of electrons is significantly increased and it is caused by development of the emission process on the cathode. In turn, it leads to increase in conduction of a discharge gap and decrease in the accelerating voltage. In this case Marx generator still worked in the mode of an aperiodic discharge, however it is rather close from border of transition to the mode of oscillations.

CONCLUSION

Data of electric measurements for all modes of a laser plasma diode are summarized in Table 1. Comparison of these data allows making the conclusion that application of magnetic insulation of electrons is proved, and discharge current in the mode 2 (see Fig. 2b) generally is determined by current of ions.

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Table 1: Summary of Modes

	Mode 1	Mode 2	Mode 3
Laser initiation	–	+	+
Magnetic field	+	+	–
Voltage	0,9 U	0,8 U	0,5 U
Discharge current	–	150 A	600 A

Thus, the experiments showed the possibility of effective ion acceleration to energy of 300 keV, when these ions were extracted from the plasma anode. The plasma is created on the anode by the radiation of a pulsed laser and allows producing ion beams with a current of more than 100 A and a current density of ~10 A/cm^2. Acceleration modes with the insulation of the electron by the field of the permanent magnet were obtained for laser-plasma diode with coaxial geometry of electrodes. It is planned to increase the accelerating voltage up to 500 kV and the energy of the laser pulse up to 1 J.

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