SMALL SIZE NEUTRON GENERATORS WITH LASER INDUCED PLASMA AND ELECTRON CONDUCTIVITY SUPPRESSED BY MAGNETIC FIELD*

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Abstract

Coaxial neutron tubes generators with transverse dimension less than 0.1 m are discussed. Laser plasma containing deuterons is created at the anode by a focused laser beam. Deuterons from plasma are accelerated by pulse voltage and produces neutrons on cylindrical cathode symmetrically surrounding the anode. Magnetic field was used to suppress knock on parasitic electron current in the accelerating gap. Computer simulation with code SUMA [1, 2] was fulfilled to investigate output neutron flow dependence on laser produced plasma density, magnetic fields and pulse voltage shapes and amplitudes, cathode and anode materials. The results obtained are in a good agreement with conducted experiments on diode with electron conductivity suppressed by magnetic field produced by permanent magnets.

INTRODUCTION

Small size pulsed neutron generators on the basis of vacuum and gas-filled pulse diode are widely used for neutron logging of oil-gas wells and ore holes, fast elemental analysis of the composition of matter, and detection and identification of dangerous hidden substances [3]. To increase the efficiency of neutron generation special methods for suppressing secondary electron emission from the cathode are used [4]. Magnetic insulation in the diode gap between the cathode and plasma anode is especially effective for diode with high accelerating voltage [5, 6]. Transverse size of those generators is very important for a lot of significant application. That is why we use permanent magnet, which is arranged inside the vacuum tube [6].

Experimental studies of neutron generation in a plasma diode with magnetic insulation of the electrons by the field of a permanent magnet were performed on a model equipped with a laser source of deuterons and an Arkad'ev–Marx generator [7, 8]. Comparison of computer simulation results on the base of code SUMA with experimental one will allow us to obtain the model for sufficient description of the process at neutron tubes.

THE EXPERIMENTAL SETUP

A sectional schematic view of the setup is shown in Fig. 1. The pressure in the working volume was ~$5 \cdot 10^{-2}$ Pa. Direct acceleration of deuterons, extracted from the laser plasma, in an electric field formed by feeding a positive high-voltage pulse to the anode, toward the cathode was accomplished in the diode. A plasma-forming target in the form of a TiD pellet was arranged on the top of the anode; the radiation from a solid-state laser with an active element based on yttrium-aluminum garnet activated by neodymium and wavelength 1.06 μm was focused onto the pellet. The power density of the laser radiation in the region of plasma formation was $5 \cdot 10^{10}$ W/cm^2; the laser pulse duration was 7 nsec. The cathode, made of a material based on NdFeB compounds, comprised a hollow cylinder with outer diameter 8 cm, inner diameter 4.5 cm, and height 4 cm. A neutron-forming target made of TiD or $(CD_2)_n$ was place on its inner surface.

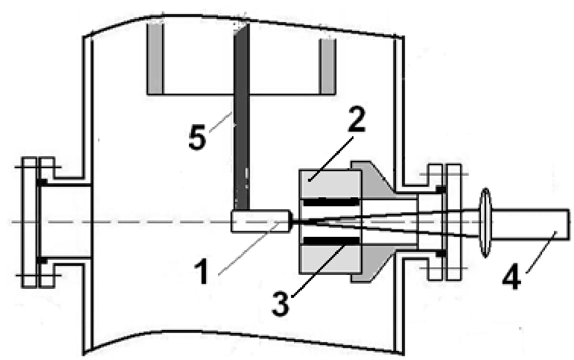

Figure 1: Laser-plasma diode. 1 − the anode with a laser TiD target; 2 – the hollow cylindrical cathode (NdFeB); 3– place target, forming neutrons (DD reaction); 4 – laser radiation; 5 – vacuum electrical connector.

COMPUTER CODE

Our main purpose was the development of suitable model and code for correct description of charge particle emission from magnetize plasma, produced by laser, theirs subsequent acceleration in electromagnetic fields and neutron production on the target.

2.5 dimensional relativistic particle in cell (PIC) code SUMA was used as a base for further improvement [1]. The code is a time dependent model that describes self consistently the dynamics of charged particles in rectangular, cylindrical, and polar systems of coordinates. The system of equations used in mathematical model consists of the Maxwell equations, the equation of the medium, and the equation of motion. At each step of the solution at running instant *t*, the charge and current densities appearing in the Maxwell equations are calculated first. The charges and current are distributed among the nodes of the spatial mesh and smoothed by weighing the areas of a

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particle (cloud) and a mesh. The arrival of new particles at a simulation step Δt to the region under investigation is simulated by the mechanism of injection, emission or secondary emission with corresponding laws of distribution.

Then the Maxwell equations are solved numerically and the resultant solution is corrected for matching to the Poisson equation. The correction is carried out by solving the Poisson equation for the difference of charge density distribution obtained from the divergence Maxwell equations and the actual distribution of charges. Poisson equation is solved using the algorithm of fast Fourier transformation in one coordinate and Thomas algorithm in the other coordinate. For a complex boundary as well as in the presence of electrodes in the domain, the capacity matrix method is used, which relates the potential and charge at the required nodes.

Since the solutions to the Maxwell equations gives the field is at the nodes of 2D mesh, the field at the intermediate points at which particles are located must be calculated for numerical integration of the equations of motion. For this purpose, interpolation and smoothing of mesh functions is used.

Integrating the equations of motion, we determine the distribution of particles in the phase space at the next instant $t + \Delta t$, and so on. For integration, the relativistic version of the method is employed with overstep using a time shift of the spatial coordinate and momentum. The particles falling on the walls of the chamber or electrodes are removed.

SIMULATION RESULTS

To simulate charge particles emissions from plasma boundaries we use experimental data for plasma velocity expansion correspond to density of the laser radiation. The delay of the accelerating voltage pulse with respect to the laser pulse was ~100 nsec. This data and the radius of laser spot on the anode allow us to make conclusion about the plasma boundary location to the moment of high voltage accelerating pulse appears in the system. As an illustration, the laser radiation pulse $U(t)$ as well as the accelerating voltage pulse $U_c(t)$ and the diode current $I(t)$, which correspond to a diode with a laser source of deuterons in a regime of magnetic insulation of electrons by the field of a permanent magnet are displayed in Fig. 2.

The plasma boundary is modeled by cylindrical surface (azimuthal symmetry case) with initial radius and length 1 mm and 2 mm accordingly. Further, the surface size is increased in transverse and longitudinal directions according to corresponding velocity value. Emission from the plasma surface is simulated by field divergence adjusted for space charge limited. Electric field distribution in diode is changing according with accelerating voltage pulse $U_c(t)$ (Fig. 2b). Electric field potential distribution in diode for the time correspond to $t = 0.5$ µsec is presented at Fig. 3. Field of permanent magnet is modeled by a set of coils, which allocated on real magnets surface. The values of coils currents are adjusted to obtain magnetic field distribution close to experimental one.

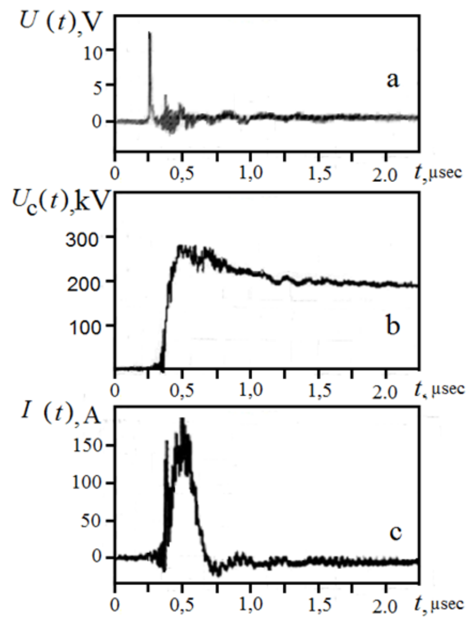

Figure 2: Laser radiation pulse (a), accelerating voltage pulse (b), and diode current pulse (c) for a diode with a laser source of deuterons in a regime of magnetic insulation of electrons.

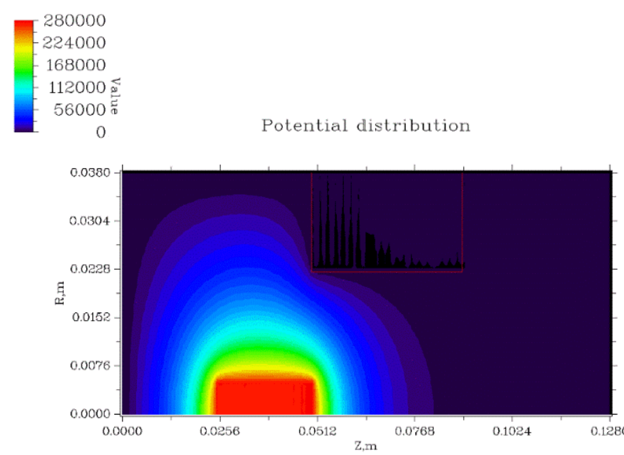

Figure 3: Potential distribution in diode.

Magnetic field distribution of NdFeB permanent magnet is presented at Fig. 4.

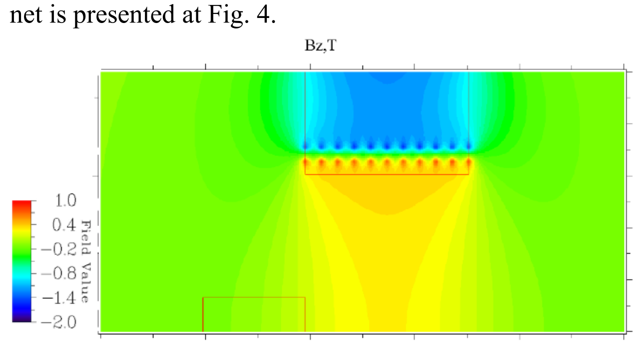

Figure 4: Magnetic field distribution in diode.

Typical charge particles and field distributions shown on Fig. 5. The electrons (red points on the figure) are produced by the secondary emission on the target.

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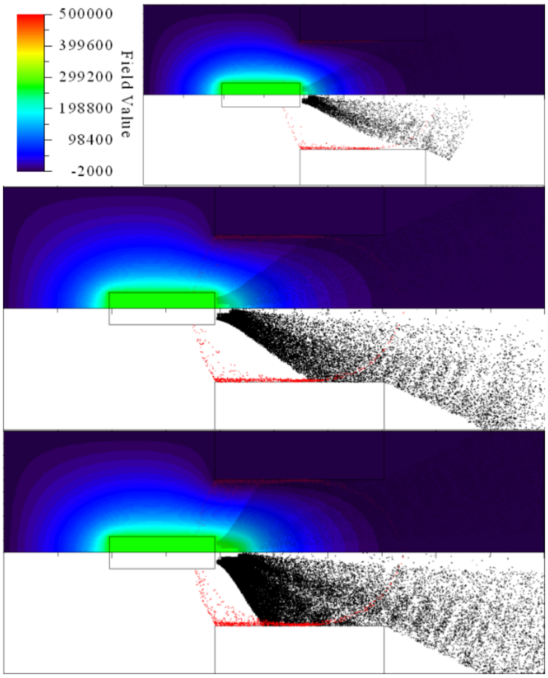

Figure 5: Field potential (upper part) and charge particle (lower part of each picture) distributions for different time moment. Deuterons - black points, electrons -red points.

The results obtained during computer simulation in a range of accelerating voltage amplitudes 120 ÷ 280 kV, allow us estimate the neutron flow from TiD target using nuclear reaction D(d,n)^{3}He. Neutron flow per pulse was calculated by the following equation:

$$f = \frac{sn}{e\tau}\sum_i q_i \int_0^{W_i} dW \frac{\sigma(W)}{F(W)}, \qquad (1)$$

where s – target stoichiometry coefficient, n – target nuclei concentration, e – elementary electric charge, q_i - deuteron charge with energy W_i, $\sigma(W)$- nuclei reaction cross-section on the target, $F(W)$ - deuteron bremsstrahlung loss in the target, τ- pulse duration.

Figure 6 shows the results of those calculations in compare with experimental one.

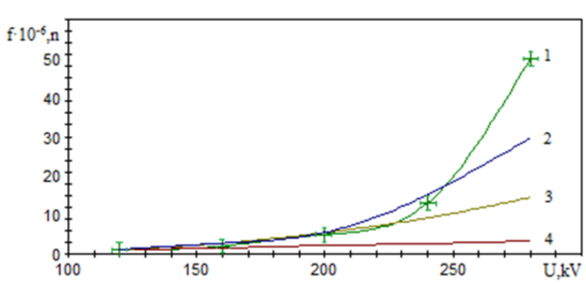

Figure 6: Neutron flow upon accelerating voltage. 1-experiment; 2 and 3-computer simulation results with and without additional emission from the target accordingly; 4-calculation from Eq. (1) without simulation.

Neutron flow calculation using Eq. (1) for preset number of deuterons (n = 0.2 10^{13}) and energy on the target eU_c (without energy spread) shown at Fig. 6 (line 4). The number of deuterons was chosen to obtain the flow value for the first point on the line 4 (U_c=120 kV) equals experimental one (line 1). Those calculations uses for rough estimation the number of deuterons, which participate in neutron production, and don’t taking in to account the deuterons emission gain from plasma surface with accelerating voltage increased. Computer simulation results (Fig. 6 - line 3) are in a good agreement with experiment in the accelerating voltage range 120 ÷ 200 kV. For values above this range the divergence rises. Experimental data analysis allows us to assume that this divergence may be deals with field emission from the flaring left edge of the target, which serve as permanent magnet support and is allocated at maximum of electric field with respect to other target points. There are many reasons in our experiment that may intensify this emission type. For example, target surface impurity, poor surface manufacturing, porous metals or oxide thin layer, additional surface heating with bombarding deuterons and so forth. Potential and charge particle distributions in diode with presence of field emission from left edge of the target shown on Fig. 7.

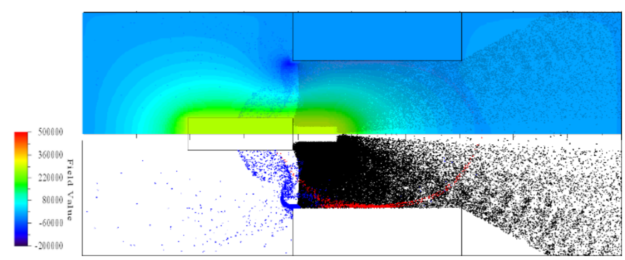

Figure 7: Electric field potential (upper) and deuterons (black points), knock on (red points) and field emission (blue points) electrons distributions (lower) in diode.

Figures 6 and 7 comparison shows that field emission from left target corner leads to significant changes of electric field distribution in the diode. Increasing of radial component of electric field on the plasma surface result in deuterons emission gain and to deuterons current rise on the target. Therefore, we observe the neutrons flow increasing (Fig. 6, line 2).

Computer simulation results analysis shows (Figs. 5 and 7) some electrons from the target get to the anode. In other words, we don’t obtain the total magnetic isolation in diode for this magnetic field configuration. Simulation gives the value of this current in order to 150 ÷ 200 A, that is in a good agreement with experiment. Nevertheless some addition steps for magnetic field optimization should be taken. It can significantly reduce electron current to anode and, as a result, increase neutron generator lifetime and efficiency. Additional simulation model modification is required especially for the future experiments with higher laser power and electric field voltage.

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