HYDROGEN NUCLIDES EXTRACTION FROM PULSE PLASMA FORMATION

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Abstract

The features of hydrogen nuclides extraction from vacuum-arc plasma and laser sources by electric field research results are presented in the report. Such sources can be used in accelerators injection systems and in neutron generators. These processes, found, are strongly influenced by electrostatic oscillations in the plasma boundary, which position continuously varies, in addition to the ions thermal motion. Such movement kinematics determined by the velocity field in plasma formation and its concentration reducing because of the ions extraction. On the basis of this model it shows that plasma boundary moves initially in the direction to the ejection electrode, then stops and begins quickly move back. An equation for the nuclides emission current density from hydrogen plasma surface for their quasiplanar extraction geometry is obtained.

At present sources of hydrogen nuclides based on an arc discharge in a vacuum or a laser-produced plasma are used in pulse neutron generators (PNG) [1,2]. PNG contains a small-sized pulsed ion diode placed in a sealed vacuum containing hollow cylindrical anode and cathode. Between them deuterons are accelerated to the maximum energy not exceeding 150 keV by a pulse electrostatic field. The operating pressure in diode's volume comprises about 10^{-2} Pa.

The reactions $T(d,n)^4He$ and $D(d,n)^3He$ undergoing inside the target located in the cavity of a cathode electrode are used for obtaining neutrons. The target represents a metal film effectively dissolving hydrogen (Ti, Sc, Zr), evaporated onto a metal substrate and containing occluded deuterium or tritium.

Fig. 1 shows the schematic section in one embodiment of the vacuum arc deuteron source (VADS) described in works [1,3].

The anode and cathode of the source in question are made of deuterated zirconium.

The processes of deuterium plasma formation are defined by properties of an arc discharge in a vacuum [3,4]. The formation of an arc is preceded by high voltage discharge in the interelectrode space. During the build-up of the discharge current under the influence of a self-generated magnetic field, pinching of the discharge channel occurs in the cathode and anode regions where current densities can exceed 10^{10} A/m^2. Fast local heating of electrodes, deuterium desorption and evaporation of the metal carrier (Zirconium) take place in the pinch zones. And in this medium the formation of an arc occurs. An ignitor discharge over the surface of a hollow disk shaped insulator is used for the enhancement of an arc.

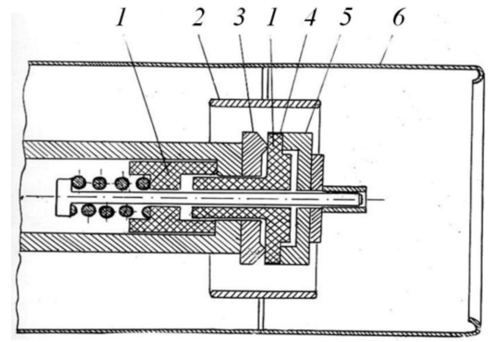

Figure 1: A three-electrode VADS: 1- insulators; 2- anode; 3- cathode; 4- semiconducting coating ; 5- igniter electrode; 6- shielding electrode

This discharge arises due to intensive field emission in the region of the triple point (insulator-metal-vacuum) characterized by abnormally high value of the electric field intensity. The breakdown of a vacuum gap between cathode and igniter electrode leads to the heating of the cathode's part followed by deuterium desorption. As a result, a partially ionized cloud of deuterium vapour rapidly spreading into the space between the cathode and anode of an ion source is formed.

The process of an arc formation is accompanied by the establishment of anode and cathode spots in the regions of its pinching over a period of time about 10^{-8} c.

The temperature of electrode spots can reach several thousand degrees. This provides a continuous deuterium desorption and evaporation of the metal carrier. After filling the discharge gap by metal pairs, they become the base medium of arcing since the ionization potential of the metal carrier is sufficiently lower than the deuterium potential. Therefore it should be assumed that the main suppliers of deuterons to VADS are not the body of an arc but its cathode and anode spots. Plasma is injected by electrode spots of an arc in the form of jets moving at a velocity of shock wave propagating in a vacuum. Estimates and the experimental data show that this velocity is equal to ~10^4 m/s [5].

The emission of laser jets by the electrode spots is a random process. There is also a significant variance of laser jets directions from pulse to pulse. However, as a result of internal anode reflections of a VAT (Vacuum acceleration tube) diode system, a laser jet is partially symmetrized.

One of the factors that shall affect the current value of deuterons extracted from VADS is the atomic weight of the metal carrier. To illustrate this effect it can be easily drawn an analogy to a simpler laser deuteron source (LDS) [1,6], which can be regarded as a physical model

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of VADS. The work [7] revealed an increasing relative yield of deuterons from a laser source with the increase in atomic weight of the metal carrier of a plasma-forming target. This is due to an decreasing the velocity of plasma expansion with the increase in atomic weight of the metal carrier, this provides better conditions for the competition of the ionization processes in an expanding plasma over the recombination processes[1].

The formation of a voltage pulse on an igniter electrode of an ion source is initiated synchronously with the formation of a high voltage pulse on the accelerating diode gap.

The extraction of deuterons from VADS and their subsequent acceleration are generally carried out in a quasi stationary state when a flight time of a deuteron in the diode gap and a characteristic time of a voltage change are substantially less than a pulse duration of the deuteron current.

The kinetic energy of a deuteron T on the cathode is proportional to potential differences U between the anode and cathode electrodes: $T=eU$, where e- is the elementary electrical charge. The maximum attainable energy is defined by the dielectric strength of a diode system and does not exceed 0.15 MeV. Deuterons in a extending plasma cloud fly at the forefront getting ahead of heavier ions of the metal carrier.

Two factors are responsible for the process of extracting deuterons from the VADS plasma. The first factor is the thermal agitation of deuterons determining the dependence of the thermocurrent density on the time t at the VADS output [1, 8]:

$$j_T(t) = en(t)\langle V_\perp(t)\rangle \qquad (1)$$

where

$$n(t) \approx \frac{N_d}{\pi R_A{}^2(b_0 + V_d t)} \qquad (2)$$

- the electron density in the region of a plasma edge, V_d is the initial velocity of a plasma front determined by the velocity of shock wave propagating in a vacuum ~10^4, N_d is the total number of deuterons in plasma at the cooling stage of its ionization state depending on the energy stored in the tank capacitor of an ion source circuit: $W_i = \frac{C_i U_i{}^2}{2}$. Here C_i~(10^{-8}-10^{-7})F is the tank capacitor in the VADS circuit, U_i~kV- its charge voltage. The cooling of an ionization state corresponds to the stage of plasma extension when a balance between the processes of recombination and ionization in its volume is established and further the number of deuterons remains more or less constant. The parameter b_0~$10a_0$ estimates the characteristic initial size of plasma formation corresponding to the completion of its ionization state cooling similar to LDS [9], a_0- the characteristic size of an electrode spot, R_A- the radius of an anode electrode,

$$\langle V_\perp(t)\rangle = 0.4\sqrt{2e\theta(t)/M_d} \qquad (3)$$

- the average, according to the Maxwell distribution, projection on normal to a plasma surface of deuteron's thermal velocity; M_d - the mass of deuteron; θ- the plasma temperature on the energy scale, eV.

Fig. 2 depicts the set of experimental dependencies N_d (C_i,U_i), obtained for VADS with electrodes from $ZrD_{1.3}$ during the measurement of VAT current characteristics and built after processing the experimental data by the method of least squares.

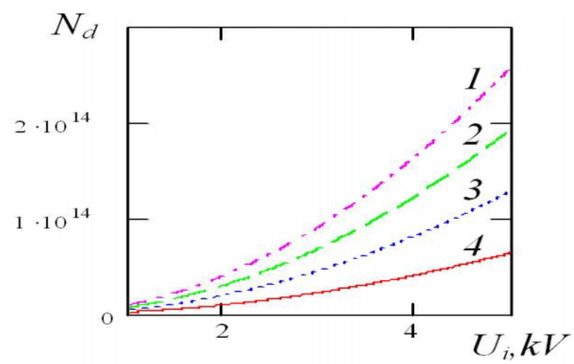

Figure 2: The characteristic set of experimental dependencies $N_d(U_i)$: 1- C_i=4.10^8 F; 2- 3.10^8 F; 3- 2.10^8 F; 4- 10^8 F;

Fig. 3 shows the results of the experiment on the neutron production.

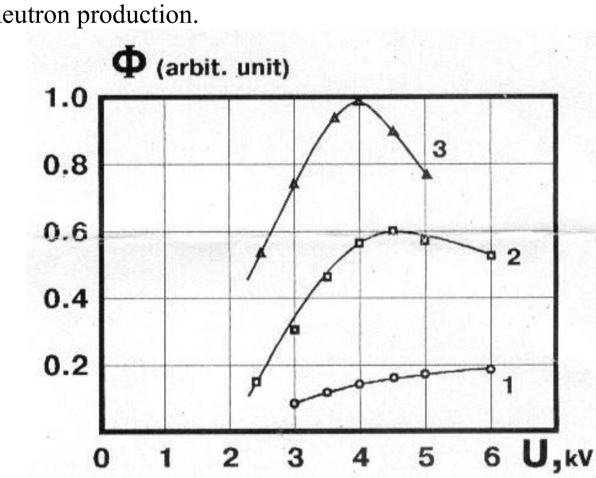

Figure 3: The characteristic set of neutron yield dependencies of PNG per a pulse (RVU) - $\Phi(U_i)$:
1- C_i=2.5·10^{-8} F; 2- 5·10^{-8} F; 3- 10^{-7} F

The monotonic disturbance of curves 2 and 3 can be explained by a limited store of energy in the tank capacitor of a high voltage circuit.

The measurement error calculated using Student's distribution with the 0.95 confidence level did not exceed 20%.

By taking a single-atomic plasma and its adiabatic expansion we find the following expression for temperature-time dependence:

$$\theta(t) \approx \theta_0 (1 + \frac{V_d t}{b_0})^{-2/3}, \qquad (4)$$

where θ_0 - the initial plasma temperature.

The second factor is related to Langmuir waves in the region being adjacent to a plasma edge [10].

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Forming a plasma jet in the region of an electrode spot, every particle of plasma will account for about an equal share of kinetic energy:

$$\frac{mV_e^2}{2} \approx \frac{M_d V_d^2}{2} \approx \frac{M_{Zr} V_{Zr}^2}{2}. \quad (5)$$

Here m, V_e; M_{Zr},V_{Zr} - the masses and maximum velocities of electrons and zirconium ions respectively.

At first electrons in the region of a plasma edge are emitted getting ahead of deuterons and forming a double layer. After being stopped, they turn back accelerating in the region of a deuteron front and rush into the depth of a plasma cloud exposing deuterons and forming a new double layer with the opposite polarization. After being stopped, electrons accelerate in the field of this double layer and run ahead again. This process is further repeated. That is the mechanism of Langmuir waves in the region of a plasma edge.

The initial length of polarization L_0 at the completion stage of an ionization state cooling can be estimated, taking into account (2), from the equation of potential (electrostatic) and kinetic energies of electrons constituting the mentioned double layer and constraints of the plasma quasi-neutrality. As a result, we have the following expression:

$$L_0 \approx \frac{V_d R_A}{e}\sqrt{\frac{\pi\varepsilon_0 M_d}{2}\frac{h_0}{N_d}}, \quad (6)$$

where ε_0 - the electric constant.

The frequency of Langmuir waves at any given time t can be estimated using the well-known formula [11]:

$$\omega_л(t) = e\sqrt{\frac{n(t)}{m\varepsilon_0}} \approx \frac{e}{R_A}\sqrt{\frac{N_d}{\pi m\varepsilon_0(b_0 + V_d t)}}. \quad (7)$$

To estimate the change of a polarization length L in the process of a plasma expansion an adiabatic invariant can be used: $L^2\omega_л$. As a result, we have:

$$L(t) \approx L_0\left(1 + \frac{V_d t}{b_0}\right)^{1/4}. \quad (8)$$

At the negative phase of Langmuir waves in the region of a plasma formation front

$$\frac{N_d L(t)}{b_0 + V_d t}$$

deuterons are exposed which can be involved in the process of acceleration. The time-averaged density of an emission current related to Langmuir waves can be estimated:

$$j_Л(t) \approx \frac{eN_d L(t)\omega_л(t)}{\pi^2 R_A^2 (b_0 + V_d t)}. \quad (9)$$

Therefore, the total density of a VADS emission current according to formulae (1)-(4) и (6)-(9) will be defined as follows:

$$j_э(t) = j_T(t) + j_Л(t) \approx$$

$$\approx \frac{eN_d}{\pi R_A^2 b_0}\left(0.4\sqrt{\frac{2e\theta_0}{M_d}} + \frac{V_d}{\pi}\right)\left(1 + \frac{V_d t}{b_0}\right)^{-5/4}\left[1 + \left(1 + \frac{V_d t}{b_0}\right)^{-1/12}\right]$$

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