

Calculated dependences of the neutron yield on the parameters of colliding plasma flows

© A.M. Zhitlukhin, N.S. Klimov, D.A. Burmistrov, V.A. Kostyushin, A.V. Lazukin

Troitsk Institute for Innovation and Fusion Research, Russian Academy of Sciences,
108840 Troitsk, Moscow, Russia
e-mail: vakostyushin@triniti.ru

Received October 23, 2024

Revised April 17, 2025

Accepted April 18, 2025

One of the tools for the formation of preheated magnetized plasma, necessary for the fusion ignition, are pulsed plasma accelerators, which have gone an impressive development path from the Marshall gun to accelerators of compact tori and plasma toroids. By colliding plasma flows and optimizing their parameters, it is possible not only to create a pulsed fusion device with a positive energy output, but also to efficiently convert their kinetic energy into the energy of linear EUF and X-ray radiation, which can lead to the development of equipment for promising technological applications and short-wave coherent directional radiation generators. The purpose of this work is to develop a simplified model and calculate the neutron yield during free passage through each other of both deuterium plasma flows and deuterium and tritium plasma flows. Based on the calculation results, the minimum values of the energy content and velocity of plasma flows are estimated, which must be provided in order to obtain the maximal values of the neutron yield. In this work, the calculations do not take into account the loss of kinetic energy of deuterons and tritons for heating the electronic component of the plasma.

Keywords: pulsed neutron source, neutron yield, plasma accelerator, kinetic model, analytical calculation.

DOI: 10.61011/TP.2025.08.61734.363-24

Introduction

A basic device for a pulsed neutron source based on a principle of colliding plasma flows is pulsed plasma accelerators. Works for their creation were launched in the late 1950s [1,2]. For accelerate matter, the first accelerators used products of explosion of metal wires that were tensioned between two extended metal electrodes to evaporate when a current pulse flowed therethrough. A cloud of metal vapor was ionized and under effect of magnetic pressure the formed plasma was accelerated towards an output end face of the accelerator. It was demonstrated that it was possible to accelerate the plasma flows to the velocities and a simple theoretical model of the plasma acceleration process was created $\sim 2 \cdot 10^7$ cm/s. In 1960, J. Marshall proposed a new design of the pulsed plasma accelerator [3], which was later named the Marshall gun. The new concept of the accelerator used a system of coaxial electrodes, while a working gas was supplied into an interelectrode gap of the accelerator by means of a quick pulse valve. It was found in the experimental studies [3] that the gun accelerated a hydrogen plasma flow of the mass of $\sim 100 \mu\text{g}$ to the velocity of $1.5 \cdot 10^7$ cm/s. The energy content of the accelerated flow was ~ 1 kJ or 40 % of the energy supplied to the accelerator. The spectral measurements showed that the plasma flow had almost no impurity of the electrode material. Using this positive experience, the early 1960s saw formulation and subsequent implementation of a design for producing high-temperature deuterium plasma by counter collision of high-velocity plasma flows in a longitudinal magnetic

field, whose induction varied from 0 to 1.2 T [4]. The accelerator-generated flows had high-velocity front parts, whose plasma density was $n \sim 10^{14} \text{ cm}^{-3}$ and which moved at the velocity of $v \sim 10^8$ cm/s, and denser ($n \sim 10^{16} \text{ cm}^{-3}$) rear parts, whose motion velocities did not exceed 10^7 cm/s. Despite the fact that for the front parts of the flows the condition $\lambda_{ii} \gg l$ is certainly fulfilled, where λ_{ii} is the mean free path of ions of one flow in the plasma of another flow, and l — is the length of the flow, a collision area exhibited formation of a „stationary“ plasma with transverse energy of the ions ~ 3 keV. Although the paper does not specify a mechanism of deceleration of such fast ions, the very fact of formability of the high-temperature plasma in the diagram of counter collision of the high-velocity plasma flows was a powerful incentive for developing research in this field. The later studies [5–7] have shown that in the presence of the longitudinal magnetic field the interpenetrating streams could develop electromagnetic instabilities, for example, a hose instability, when a directed energy of the streams is effectively thermalized as a result of ion scattering on progressing Alfvén oscillations. It was determined by computational calculations of dynamics of turbulent relaxation of supersonic streams in the paper [8,9] that the first stage includes deceleration of the streams and the directed ion energy transfers into the particle oscillation energy in the Alfvén-wave field. Then the particle energies equalize by degrees of freedom. At this, the full time of thermalization does not exceed the magnitude $\frac{10}{\omega_{Bi}}$, where ω_{Bi} is an ion cyclotron frequency. The instability is developed with fulfillment of the condition $\frac{v}{v_A} > \frac{1}{\sqrt{2}}$,

where v is the stream velocity, v_A is the Alfvén velocity. It is shown in the experiments [10] that it is possible to implement effective thermalization of the directed energy of the plasma streams by transmission of a longitudinal electric current's pulse along the plasma surface.

The second half of 1960s and in the early 1970s saw many studies of the pulsed plasma accelerators [11–21]. Based on the results of these studies, physical models were created to evaluate acceleration of the plasma in the low-power pulsed plasma accelerators, like, for example, the model of a thin non-deformable plasma shell, which in motion in the interelectrode gap scoops and captures a neutral gas in front of it [22].

Starting from the mid 1970s, it was a start of works for developing powerful pulsed electrodynamic plasma accelerators and studying dynamics of interaction of their generated plasma flows with magnetic fields. Within the framework of these works, National Research Centre "Kurchatov Institute" (presently, State Scientific Center of Russian Federation Troitsk Institute of Innovative and Thermonuclear Research) has created an experimental complex 2MK-200 [23]. The complex was equipped two high-voltage low-inductance capacitor accumulators with capacitance of $576\mu\text{F}$ per each and charging voltage of up to 50 kV for powering the accelerators, two capacitor accumulators of $60\mu\text{F}$ per each and charging voltage of up to 50 kV for pre-ionization of the neutral gas in the interelectrode gaps of the accelerators and an accumulator of 0.18 F and the charging voltage of 5 kV for powering solenoids which form the magnetic field in plasma wires and a plasma flow collision chamber. Later [24], the complex was modernized. The capacitance of the accelerator-powering accumulators was increased to $1150\mu\text{F}$, which corresponded to their stored energy of 1.44 MJ with the charging voltage of 50 kV, while the capacitance of the solenoid-powering capacitor accumulator was increased to 0.27 F. After the modernization, the total available power of the complex exceeded 6 MJ.

The interelectrode gaps of the powerful plasma accelerators were filled with the gas by means of fast-acting electrodynamic gas injectors [25] designed to supply hydrogen at the rate of 350 g/s at the initial gas pressure of 10^7 Pa in a valve cavity. The full opening time of the valve did not exceed $200\mu\text{s}$.

In order to study the plasma parameters and characteristics of neutron and X-ray radiation, the installation 2MK-200 was equipped with a respective set of diagnostic means [26].

Already at the early stage of studies of the pulsed plasma accelerators of the Marshall gun type, it was shown that in order to achieve high efficiency of conversion of the capacitor-stored energy, the plasma-flow energy should have been matched with a geometry of the electrode system of the accelerator, so should a mass of the accelerated flow with the parameters of the power supply. In the first approximation, this match condition may be an equality of the half-period of the discharge current pulse and the time of flight of the flow along the electrode system of the

accelerator:

$$\pi\sqrt{LC} \approx \frac{2l}{v},$$

where L — the inductance of a discharge circuit, which includes full inductance of the interelectrode gap, C — the capacitance of the accelerator, l — the length of the electrode system, v — the velocity of the flow at the accelerator output. By means of simple transformations, the match condition can be reduced to the following form:

$$U \approx \frac{\pi v^2}{2} \sqrt{\frac{m}{l}} \frac{dL}{dz}.$$

It follows from this expression that at the pre-defined values of the flow mass and its velocity the accelerators of the Marshall gun type can reduce the charging voltage of the accelerator only by increasing the accelerator length and decreasing linear inductance of the electrode system, which can be calculated as inductance of a coaxial conductor:

$$\frac{dL}{dz} = 2 \cdot 10^{-7} \ln\left(1 + \frac{\delta}{r_1}\right),$$

where δ — the value of the interelectrode gap, r_1 — the radius of the accelerator electrode. The value of the interelectrode gap has a limitation below, which is determined by electrical strength of the gap and it is about 4 cm. As will be shown below, to achieve high neutron yield it is necessary to reduce an area of the flow cross section. Therefore, it is irrational to greatly increase the value of the radius of the internal electrode. Based on the above considerations, we assume that $r_1 = 11\text{ cm}$ and the length of the electrode system is 4 m. We evaluate the required value of the charging voltage of the accelerator-powering accelerator designed for generating the plasma flow with the energy content of 500 kJ at the two values of the flow velocity (the deuteron energy): $3 \cdot 10^5\text{ m/s}$ ($E_d = 0.98\text{ keV}$) and $1 \cdot 10^6\text{ m/s}$ ($E_d = 10.4\text{ keV}$). The first case requires a capacitor accumulator with the charging voltage of $U_0 = 58\text{ kV}$, while the second case requires the same with the charging voltage of $U_0 = 640\text{ kV}$. The capacitor accumulator with $U_0 = 58\text{ kV}$ and the energy content of $W \sim 1\text{ MJ}$ is realistic, but creation of the capacitor accumulator with $U_0 = 640\text{ kV}$ is a task that is almost impossible to realize. Based on these estimates, the works for creating neutron radiation sources and fusion installations using the pulsed plasma accelerators proceeded in two directions.

The essence of the first direction (Magneto-Inertial Fusion or Magnetized Target Fusion) means proceeding to a two-stage diagram, whose first stage includes application of the pulsed plasma accelerators or lasers to create the plasma that is pre-heated to 1–2 keV. In the second stage, this plasma is held and additionally heated by powerful neutral beams as in TAE Technologies [27] or additionally compressed and its temperature is brought to the level, at which there are intense synthesis reactions, as it is planned to be realized in General Fusion [28] and Helion

Energy [29]. All these installations use compact tori or FRC (Field-Reverse Configurations) [30–34] as the plasma flows. This direction may also include experiments in the installation Z in the Sandia National Laboratory, USA [35], which achieved the D-D neutron yield of 1.1×10^{13} per pulse, while the initial plasma inside a liner was created by means of the powerful pulsed laser. The exhaustive review of the works for this direction is given in the paper [36].

The second direction included optimization of the pulsed plasma accelerators, which would allow increasing the efficiency of the accelerators at the lesser charging voltages of the capacitor accumulators. The optimization was based on the following considerations. If the motion of the plasma flow is significantly decelerated at the initial stage of acceleration, then it is possible to pump the main part of the energy stored in the capacitance accumulator into inductance of the discharge circuit and initial inductance of the accelerator. Then this energy is spent for accelerating the flow at the shorted capacitor accumulator. In a limit, the accelerator efficiency can achieve the magnitude

$$\eta = \frac{L_a}{L_C + L_0 + L_y},$$

where L_a — the inductance of the electrode system from a breakdown location to the end face of the electrodes, L_C — the inductance of the capacitor battery and the cable line, L_0 — the inductance of the electrode system from the insulator to the breakdown location. Since $L_a \gg L_C + L_0$, then in this case the accelerator efficiency will significantly exceed 50%. The studies [37,38] have investigated the electrode-system accelerator, whose linear inductance smoothly varied from $1.9 \cdot 10^{-8}$ H/m at the initial portion of the electrode system to $6.2 \cdot 10^{-8}$ H/m at its output portion. The experiments have shown that at the velocities of the plasma flows $(2-4) \cdot 10^7$ cm/s the accelerator with such an electrode system had higher efficiency as compared to the accelerator whose electrode system had linear inductance of $6 \cdot 10^{-8}$ H/m at the initial portion. But in the modes, when the velocity of the plasma flows increased to 10^8 cm/s, the accelerator efficiency sharply dropped to several percent [39]. It was formulated to propose to use a magnetic shutter that would hinder motion of the plasma flow at a front of the discharge current pulse [40]. However, this proposition is acceptable only for the low-power accelerators, wherein solenoid-created inductance of the magnetic field in the shutter did not exceed 7–10 T.

The 1990s saw continuation of detailed studies of the pulsed plasma accelerators of the traditional design of the Marshall gun type [41]. They included both the experimental studies and numerical simulation of plasma acceleration and dynamics of impurities. These studies again confirmed an unstable nature of plasma acceleration in the traditionally-designed pulsed plasma accelerators. These instabilities have developed to result in incomplete scooping of the working gas, thereby resulting in repeated bridgings

of the interelectrode gap behind the accelerated plasma shell. Due to repeated breakdowns, the velocity of the flow at the accelerator output decreased and its length increased and a strong uniformity of the directed velocity along the flow length occurred. Along with the previous studies [42–46], these studies have again confirmed the fact that the traditionally-designed pulsed electrodynamic plasma accelerators were quite effective to fill fusion traps or to form the pre-heated plasma for the two-cascade diagram of the pulsed neutron source. However, in order to create effective neutron-radiation sources based on the principle of counter collision of the high-velocity plasma flows of high energy content, it is necessary to drastically modernize the traditional pulsed plasma accelerators.

C. Hartmann and J. Hammer (Livermore Laboratory, USA) have developed a fundamentally new diagram of the pulsed plasma accelerator [47], wherein along with transfer to acceleration of plasma toroids, it also included a stage of their preliminary compression. This stage allowed increasing the accelerator efficiency and increasing the time of current rise. The latter is important both in terms of reduction of the power of the accelerator power supply and for reduction of intensity of shock waves in the accelerated plasma, which is necessary for maintaining a correct magnetic configuration of the accelerated flow for the entire time of acceleration. With the available power of 0.26 MJ, the „RACE“ (Ring ACceleration Experiment) installation designed by this diagram has achieved record-breaking velocities of the plasma flows $3 \cdot 10^6$ m/s, but with these velocities the accelerator efficiency did not exceed 10% [48]. Another problem was detected in the studies by the „RACE“ installation. When transiting to low masses of accelerated matter due to efforts to achieve high velocities with the small energy content of the flow, the impurities that were uncontrollably emitted from the electrode surfaces began significantly affect the flow parameters, thereby preventing calculated velocities at the accelerator output. It was showed later that the latter problem was inherent to the low-power accelerators only. The experiments that were carried out in the USA Phillips Laboratory within the framework of the „MARAUDER“ program (Magnetically Accelerated Ring to Achieve Ultra-high Directed Energy and Radiation) [49] have demonstrated not only operability of the plasma toroid accelerator with available power of up to 4 MJ, but effective compressibility of these toroids in cone electrode systems with almost no impurity problem.

RF SSC TRINITY has also designed a new type of the pulsed plasma accelerator [50] that was abbreviated as PTPA (plasma-toroid pulsed accelerator). A main PTPA novelty was that a quasi-steady-state azimuthal magnetic field (similar to the toroidal field in the tokamak chamber) was preliminarily created in the interelectrode gap of the accelerator. After that the cloud of a neutral gas was supplied into the interelectrode gap by means of a pulsed gas valve. By means of an inductor, which was a single-turn coil above the external electrode, a ring breakdown was initiated in the neutral gas. As a result, the plasma

toroid that was similar to a plasma tokamak cord and had the magnetic field frozen into it as it was being formed in the PTPA interelectrode gap, while this field had a toroidal and a poloidal component. In order to accelerate this toroid to the output end face of the accelerator, fast-acting pulsed switches were taken to connect the high-voltage capacitance accumulator, whose discharge current attenuated the toroidal magnetic field in front of the toroid. The performed calculations and the preliminary experiments have shown [51] that the PTPA had high efficiency due to the fact that the discharge of the capacitor accumulator is carried out to time-decreasing inductance.

The above-designed installations can be considered as the first step in modernization of the pulsed plasma accelerators, which is aimed at creating effective neutron sources based on the accelerated plasma streams. This step was enough to show that there are not simple science-technology solutions which could quickly result in creating an effective device for forming and accelerating compact plasma formations to the high velocities and a significant volume of research is needed to achieve the set goal.

At this stage of research, development of the newly-designed pulsed plasma accelerators with higher efficiency does not mean complete rejection of the traditionally-designed accelerators. There are two reasons for this. The first reason is that it is not always required to obtain record-breaking yields of neutron (or X-ray) radiation and it is profitable to sacrifice the accelerator efficiency in favor of simplicity and cheapness of the device. Secondly, based on the classic accelerators, it is possible to realize a flight diagram of the neutron source, which has a number of obvious advantages.

1. In the counter collision, the energy of relative motion of the interacting particles exceeds their kinetic energy in four times, thereby making it possible to achieve maximum efficiency of the source with lesser values of the velocities of the plasma flows.

2. In the diagram with the counter collision, a specific function of velocity distribution of the particles ensures 4-times higher neutron yield at the ion energies exceeding 10 keV as compared to the plasma installations with realized Maxwell velocity distribution of the particles. This circumstance is especially significant when the deuterium plasma flow collides with the tritium plasma flow.

3. If the designed neutron source is considered as an external source for the subcritical nuclear reactor, then the neutron-radiating volume can have small transverse sizes and can be arranged as a cylindrical channel that is surrounded by a blanket. At the same time, the very accelerators with their power supplies will be far away from ionizing radiation sources.

4. By varying the length of the colliding flows and the plasma density in them, it is possible to achieve conditions, in which the colliding flows will fly through each other, thereby taking away the main portion of the kinetic energy from the blanket zone and distributing it along the large surface of the vacuum chamber. At the same time, an

energy price of the neutron will remain at an acceptable level.

5. The proposed device is not designed to hold the high-temperature plasma and does not require creation of the magnetic field a complex configuration in the collision zone. The longitudinal magnetic field created in the cylindrical channel is used mainly for reducing thermal fluxes from the area of interaction of the plasma flows to a channel wall. And, in principle, its presence is not mandatory for achieving high neutron yield.

6. The chamber of the neutron generator has a simple cylindrical form and, if damaged, it can be easily replaced without disassembling the blanket.

By summarizing the above-given brief analysis of global works for creation of the pulsed neutron-radiation sources, it is logical to conclude as follows. Along with the leading directions for implementing the controlled nuclear fusion reaction with the positive energy yield based on the tokamaks and the powerful pulsed lasers, there is still quite intense development of alternative approaches. One of these approaches is to implement a fusion ignition when compressing the pre-heated magnetized plasma. One of the tools for forming this plasma is the pulsed plasma accelerators. Presently, for the most advanced of them, the energy content of the generated plasma flows is brought to several megajoules, while the velocity of the flows exceeds 10^6 m/s. With the said parameters of the plasma flows, the modern plasma accelerators are quite promising devices. In the quite compact devices created based thereon, in the counter collision diagram, it is possible to achieve the neutron yields of the synthesis reaction, which are record-high for the pulsed electrotechnical systems.

For the most successful and effective creation of these systems, designing new samples of experimental equipment and performance of the experiments was preceded by carrying out respective simulation and computation-theoretical activity. The present study provides a description of the simplified model and results of estimated calculations of the neutron radiation yield in a free flight through each other both of the deuterium plasma flows and the deuterium and tritium plasma flows. The results of the calculations are taken to determine the minimum values of the energy content and the velocities of the plasma flows that shall be provided to obtain the planned values of the neutron yield.

1. Simplifications taken during the calculations

The calculations are carried out for the case when the plasma flows freely fly through each other. It is possible only when there is no frozen magnetic field in the colliding plasma flows or it has only the longitudinal component B_z . The following simplifications are also used when carrying out the calculations:

- 1) the thermal energy of the flow plasma is neglected. It is considered that the full energy of the colliding flows is

equal to their kinetic energy. This simplification is based on the experimentally-established fact that plasma flows generated by the pulsed plasma accelerators are supersonic and the condition that the Mach number $M \gg 1$ is fulfilled for them;

2) it is assumed that when the ion components of the counter flows move through each other the instabilities do not develop and the condition $\lambda_{dd} \gg l$ is fulfilled, i.e. the deuterons of one flow fly through another flow without significant scattering;

3) in the collision of the flow, their electron components stop and do not penetrate into each other due to a small energy of electrons and, therefore, a small path length of the electrons as compared to the flow length $\lambda_{ee} \ll l$. With mutual penetration of the deuterons, compression waves propagate along the electron components of both the flows. Since in this case the thermal velocity of the electrons $v_e \ll v$, then the compression process is adiabatic. In the first flow, the electron density increases in $(1 + n_2/n_1)$, while in the second flow it increases in $(1 + n_1/n_2)$, where n_1, n_2 are the flow densities. With adiabatic compression, the electron heating is determined by the relationship

$$T_e = T_{e0} \left(\frac{n_e}{n_{e0}} \right)^{\gamma-1},$$

where $\gamma = 5/3$, n_e, n_{e0} are a current and an initial electron density. This implies that even when the plasma density in one of the colliding flows is in 100 times higher than the plasma density in another, then the plasma electron temperature in a zone of the lesser plasma density increases due to the kinetic energy of the dense flow only in 21.7 times. As it is assumed that the initial value of the thermal energy of the plasma is negligible as compared to the energy content of the flow, then at the present stage of estimation we neglect a loss of the kinetic energy of the ion components for compression of the electron component in the calculations.

2. Performing the estimated calculations of the neutron yield provided that the flow velocities are equal

Let us consider the collision of the two deuterium plasma flows. First of all, we consider a special case, when the flows have the same cross-sectional area ($S_1 = S_2 = S$), the same energy content ($W_1 = W_2 = W$) and the same plasma density in them ($n_1 = n_2 = n$). It follows from the above-given conditions that the flows have the same length ($l_1 = l_2 = l$) and contain the same number of the deuterons. In the laboratory system of coordinates, the energy of the deuteron in the first flow E_{d1} is equal to the energy of the deuteron in the second flow E_{d2} and is $E_d = 1/4 E_{d12}$, where E_{d12} is the deuteron energy of one of the flow in the system of coordinates, in which the second flow is at rest. In the first approximation, we will calculate the neutron yield

of the flows, which move towards each other at the same velocities v .

For calculation of the neutron yield, we use a formula for a section of the $D-D$ -reaction from the study [52]. Taking into account the fact that reactions in deuterium proceed almost in equally-probable ways, the value of the section of the synthesis reaction, wherein the neutron yield is observed, takes the following form (1):

$$\sigma_{DD} = 1.2 \cdot 10^{-19} \frac{1}{E_{d12}} e^{\frac{-1.4 \cdot 10^3}{\sqrt{E_{d12}}}}. \quad (1)$$

The average length to be travelled by the deuteron in the deuterium plasma to implement an event of its merge with another deuteron, with the neutron yield, is formularized: $\lambda_{DD} = 1/(n_2 \sigma_{DD})$. This implies that with flight of the deuteron of the first flow through the second flow probability of the event of the reaction of the $D-D$ -synthesis is $P_{DD} = l/\lambda_{DD} = l n_2 \sigma_{DD}$. Accordingly, in flight of the flows through each other the full neutron yield is determined by the formula (2):

$$N_{DD} = N_1 n_2 l \sigma_{DD} = 1.2 \cdot 10^{-19} \frac{N_1 n_2 l}{E_{d12}} e^{\frac{-1.4 \cdot 10^3}{\sqrt{E_{d12}}}}. \quad (2)$$

We multiply and divide the right hand part of the relationship (2) by S and in it, instead of E_{d12} , we substitute its expression via the energy of the deuteron in the laboratory system of coordinates $E_{d12} = 4E_d$. Further on, when taking into account that $n_2 l S$ is equal to the total number of deuterons in the second flow N_2 and $N_1 = N_2 = N$ we obtain the following expression for the neutron yield (3):

$$N_{DD} = 3 \cdot 10^{-20} \frac{N^2}{S E_d} e^{\frac{-700}{\sqrt{E_d}}}. \quad (3)$$

And, finally, using the expression $N = W/E_d$ and transiting to a Joule as a unit of measurement of the energy content of the plasma flow in the laboratory system of coordinates (4), we obtain a final form of the formula for the neutron yield in the counter collision of the identical deuterium plasma flows:

$$N_{DD} = 1.17 \cdot 10^{18} \frac{W^2}{S E_d^3} e^{\frac{-700}{\sqrt{E_d}}}, \quad (4)$$

where W — [J], E_d — [eV], S — [cm²].

Fig. 1 shows the curve of the dependence of the neutron yield on the energy of the deuteron in the laboratory system of coordinates when $W = 160$ kJ and $S = 30$ cm². The curve has the maximum when $E_d = 13.6$ keV, which corresponds to the velocity of motion of deuterons in the laboratory system of coordinates, which is equal to $1.14 \cdot 10^8$ cm/s. In this point the yield is $0.98 \cdot 10^{12}$ $D-D$ -neutrons per pulse. Reduction of the yield with decrease of the deuteron energy is explained by predominance of decrease of the nuclear fusion reaction section over increase of the number of deuterons in the flows. And, vice

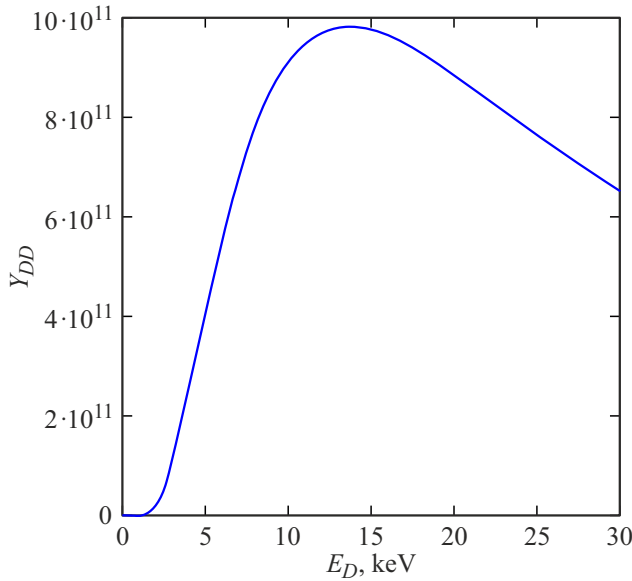


Figure 1. Dependence of the D – D -neutron yield on the energy of the deuteron in the laboratory system of coordinates for $W = 160$ kJ and $S = 30$ cm².

versa, reduction of the yield with increase of the velocity is explained by predominance of the number of deuterons over increase of the nuclear fusion reaction section. With decrease of the velocity of the flows to $8 \cdot 10^7$ cm/s, the neutron yield is reduced not more than by 20 %. The said circumstance is quite important for practical implementation of the neutron source based on the counter collision of the plasma flows, since it is experimentally found [2] that the efficiency of the classically-designed pulsed plasma accelerators substantially drops with increase of the velocity of plasma flows generated by it.

It follow from the formula (4) that the value of the neutron yield does not depend on the length of the plasma flow and is proportional to the square of the energy content of the flow and inversely proportional to the area of its cross section. It follows from the quadratic dependence of the value of the neutron yield on the energy content of the flow that with increase of the energy content of the flows the energy price of the neutron will decrease according to the formula (5):

$$W_{ndd} = \frac{2W}{1.17 \cdot 10^{18} \frac{W^2}{SE_d^3} e^{\frac{-700}{\sqrt{E_d}}}} = 1.71 \cdot 10^{-18} \frac{SE_d^3}{We^{\frac{-700}{\sqrt{E_d}}}}, \quad (5)$$

where W — [J], E_d — [eV], S — [cm²].

By substituting E_d that is equal to 13.6 keV and $S = 30$ cm² into the formula (5), we obtain the following formula for the energy price of the D – D -neutron with the optimum value of the energy of the deuteron (6):

$$W_{nDD_{opt}} = \frac{5.22 \cdot 10^{-2}}{W}. \quad (6)$$

With the energy content of the plasma flows, which is equal to 1.6 MJ, which corresponds to the yield of 10^{14} D – D -neutrons per pulse, the energy price of the D – D -neutron will be $2 \cdot 10^5$ MeV per neutron.

We will carry out similar estimated calculations for the case when the deuterium plasma flow collides with the tritium plasma flow and determine conditions, at which there is the maximum D – T -neutron yield per pulse for the flows that have the same energy content. For this, we will use an analytical expression for the D – T -reaction section from the paper [52]:

$$\sigma_{DT} = \frac{6 \cdot 10^{-17}}{E_{dt}} \frac{e^{\frac{-1.5 \cdot 10^3}{\sqrt{E_{dt}}}}}{\left[1 + \frac{(E_{dt} - 10^5)^2}{3 \cdot 10^{10}}\right]}, \quad (7)$$

where E_{dt} is in [eV].

By following the previously-selected logic of presentation, in the first stage we consider a case when the flows have the same cross-sectional area and the same energy content. The flows move towards each other at the same velocities and have the same length. It follows from the above-mentioned conditions that due to a difference in the masses of deuteron and tritons in the flow $N_t = \frac{m_d}{m_t} N_d = 0.67 N_d$ and, respectively, $n_t = 0.67 n_d$. In the laboratory system of coordinates, the energy of the deuteron $E_d = \frac{1}{4} E_{dt}$.

Similar to the above-considered variant of collision of the deuterium flows, the average length to be travelled by the deuteron in the deuterium plasma to implement the event of its merge with the triton is formularized: $\lambda_{DT} = 1/(n_t \sigma_{DT})$. This implies that with flight of the deuteron through the tritium flow probability of the event of the D – T -synthesis reaction is $P_{DT} = l/\lambda_{DT} = l n_t \sigma_{DT}$. We multiply and divide the right hand part of the relationship (7) by S and instead of E_{dt} we substitute its expression via the energy of the deuteron in the laboratory system of coordinates $E_{dt} = 4E_d$. The product $n_t l S$ is equal to the full number of tritons in the second flow and by replacing $n_t l S$ with N_t and using the relationships $N_t = 0.67 N_d$ and $N_d = W/E_d$, we obtain

$$N_{DT} = \frac{10^{-17}}{SE_d^3} \frac{W^2}{\left[1 + \frac{(4E_d - 10^5)^2}{3 \cdot 10^{10}}\right]} e^{\frac{-750}{\sqrt{E_d}}}.$$

By transiting to the energy content of the plasma flows in the laboratory system of coordinates in Joules, we obtain the final form of the formula for the neutron yield in the counter collision of the deuterium plasma flow with the tritium plasma flow:

$$N_{DT} = \frac{3.91 \cdot 10^{20}}{SE_d^3} \frac{W^2}{\left[1 + \frac{(4E_d - 10^5)^2}{3 \cdot 10^{10}}\right]} e^{\frac{-750}{\sqrt{E_d}}}, \quad (8)$$

where W is the kinetic energy of each of the flows in [J], E_d in [eV], S in [cm²].

Fig. 2 shows the curve of the dependence of the D – T -neutron yield on the energy of the deuteron, which corresponds to the formula (8). As in the case of collision

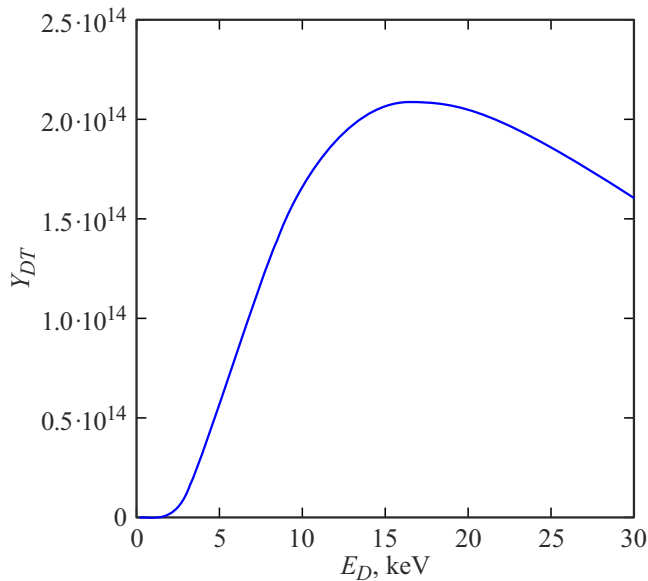


Figure 2. Dependence of the $D-T$ -neutron yield on the energy of the deuteron in the laboratory system of coordinates.

of the two deuterium plasma flows, the shown curve has a maximum. However, its position has been shifted to the higher values of E_d and it is at $E_d = 17.2$ keV. With the said value of E_d , the neutron yield is $2.08 \cdot 10^{14}$ $D-T$ -neutrons, i.e. it is in 212 times higher than in the case of the counter collision of the deuterium plasma flows. As in the case of the collision of the deuterium plasma flows, a drop of the neutron yield towards simultaneous decrease of the velocities of the flows (and the respective energies of the deuteron and the triton) is quite smooth. With reduction of the energy of the deuteron from 13.6 to 6.9 keV, the $D-T$ -neutron yield decreases in no more than two times.

With the previously-assumed limitations due to limit capabilities of the modern plasma accelerators, we consider that E_d does not exceed 13.6 keV, and E_t does not exceed 20.4 keV. Both the values correspond to the same value of the particle velocity of $1.14 \cdot 10^8$ cm/s. With this value of the velocity, the neutron yield is $1.99 \cdot 10^{14}$ $D-T$ -neutrons per pulse.

In order to determine the energy price of the neutron, we divide the total energy content of the plasma flows by the value of the $D-T$ -neutron yield per pulse. Using the value $E_d = 17.2$ keV, we obtain the following expression for the energy price of the $D-T$ -neutron as a function of the energy content of the flows:

$$W_{nDT} = 8.46 \cdot 10^{-6} \frac{S}{W}, \quad (9)$$

where S in $[\text{cm}^2]$ and W and W_{nDT} in $[\text{J}]$.

With the cross-sectional area of the flows of 30 cm^2 and the energy content of the plasma flows, which is equal to 1.6 MJ, which corresponds to the yield of $2.08 \cdot 10^{16}$ $D-T$ -neutrons per pulse, the energy price of the $D-T$ -neutron

will be $9.91 \cdot 10^2$ MeV per neutron. By using the formula (9), we will determine a value of the energy content of the plasma flows from which the energy price of the neutron will be below 100 MeV/neutron (or $1.6 \cdot 10^{-11}$ J/neutron). From the inequality: $1.6 \cdot 10^{-11} > 8.46 \cdot 10^{-6} S/W$ the sought-for condition follows:

$$W > 5.29 \cdot 10^5 S, \quad [\text{J}]. \quad (10)$$

It follows from the condition (10) that with the cross-sectional area of the flow, which is equal to 30 cm^2 , the energy price of the $D-T$ -neutron will be below 100 MeV when $W \geq 16$ MJ. It should be noted that at this the neutron yield will exceed $2.08 \cdot 10^{18}$ $D-T$ -neutrons per pulse. With the same parameters of the flows in a collision of the deuterium flow with the deuterium flow, the neutron yield is $\sim 10^{16}$ $D-D$ -neutrons per pulse.

3. Performing the estimated calculations of the neutron yield in a collision of the flows with different velocities

Let us review a more general case when the colliding flows have the same energy contents and the same cross-sectional areas, but their motion velocities are unequal. First, we will calculate for a variant of collision of the deuterium plasma flows. In this case, in the formula (2) we will express the relative energy E_{d12} via the energies of the deuterons in the laboratory system of coordinates E_{d1} and E_{d2} . For this we use the following relationship:

$$E_{d12} = \frac{1}{2} m_d (v_{d1} + v_{d2})^2, \quad (11)$$

where v_{d1} and v_{d2} are the velocities of the first and second deuterium plasma flows in the laboratory system of coordinates. By substituting the expressions $v_{d1} = \sqrt{\frac{2E_{d1}}{m_d}}$ and $v_{d2} = \sqrt{\frac{2E_{d2}}{m_d}}$ into the formula (11), multiplying and dividing the right hand part of (2) by S and replacing $n_2 l S$ with N_2 , and then replacing N_1 and N_2 with $\frac{6.25 \cdot 10^{18} W}{E_{d1}}$ and $\frac{6.25 \cdot 10^{18} W}{E_{d2}}$, respectively, where W in $[\text{J}]$ and E_{d1} and E_{d2} in $[\text{eV}]$, we obtain the following formula for determining the $D-D$ -neutron yield as a function of energies of the colliding deuterons:

$$N_{DD} = 4.69 \cdot 10^{18} \frac{W^2}{SE_{d1}E_{d2}(\sqrt{E_{d1}} + \sqrt{E_{d2}})^2} e^{\frac{-1.4 \cdot 10^3}{(\sqrt{E_{d1}} + \sqrt{E_{d2}})}}, \quad (12)$$

where W in $[\text{J}]$ and E_{d1} and E_{d2} in $[\text{eV}]$, S in $[\text{cm}^2]$.

We limit values of the deuteron energy by the value $E_d = 13.6$ keV (which corresponds to the value $v_d = 1.14 \cdot 10^8$ cm/s), at which it is still possible to count on high efficiency of the pulsed plasma accelerators and consider a behavior of the neutron yield with independent variation of the deuteron energy. Due to a symmetry of a problem for calculating the value of the neutron yield at the

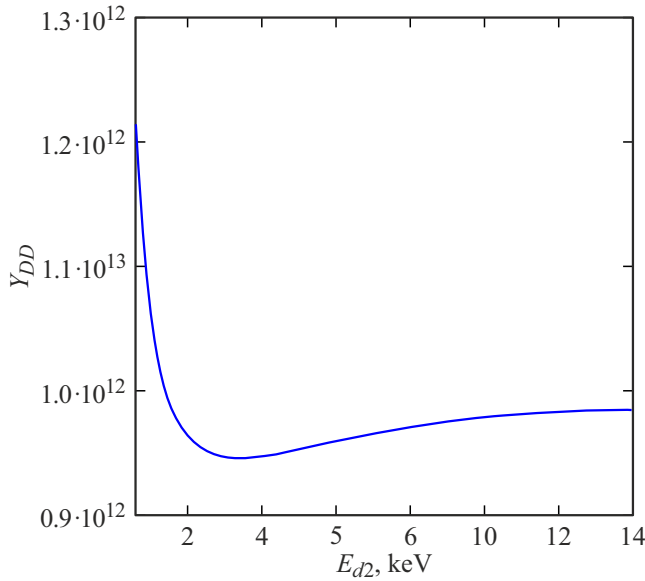


Figure 3. Dependence of the D – D -neutron yield on the deuteron energy of the counter flow when $W = 160$ kJ, $S = 30$ cm².

various values of the energy of the colliding deuterons, it is sufficient to fix the deuteron energy of one of the flows at a value that corresponds to the maximum neutron yield and to vary the value of the deuteron energy of the counter flow. For this, we substitute the value of 13 600 eV instead of E_{d1} into the formula (12) and obtain the following relationship:

$$N_{DD} = 3.45 \cdot 10^{14} \frac{W^2}{SE_{d2}(1.17 \cdot 10^3 + \sqrt{E_{d2}})^2} e^{\frac{-1.4 \cdot 10^3}{(1.17 \cdot 10^2 + \sqrt{E_{d2}})}}, \quad (13)$$

Formally, it follows from the formula (13) that with decrease of E_{d2} the neutron yield can increase to infinity. It is confirmed in Fig. 3 by a curve of the dependence of the neutron yield on E_{d2} with the following parameters of the colliding flows: $W = 160$ kJ, $S = 30$ cm². The curve of Fig. 3 shows that there is a local maximum of the value of the neutron yield at the value $E_{d2} = 13.6$ keV, in which the D – D -neutron yield is $0.98 \cdot 10^{12}$ per pulse. With decrease of the energy E_{d2} , the D – D -neutron yield decreases and at $E_{d2} = 3.38$ keV it reaches a minimum value of $0.95 \cdot 10^{12}$ per pulse. Then, with further decrease of E_{d2} , the neutron yield, calculated by the formula (23) that does not take into account losses of the deuteron energy for heating the electrons, starts increasing. When $E_{d2} = 1.6$ keV it again reaches the value of $0.98 \cdot 10^{12}$ D – D -neutrons per pulse, and when $E_{d2} = 0.6$ keV it increases to $1.21 \cdot 10^{12}$ D – D -neutrons per pulse.

It should be noted that based on such simple estimates it is impossible to conclude that at the values of the energy of the plasma streams, which are at least 50 kJ, variation of the deuteron energy of the second plasma flow can provide the neutron yields that are higher than those followed from the formula (6). The matter is that as E_{d2} decreases, the number of deuterons increases, so does its respective number of

electrons in the second flow. When $E_{d2} = 100$ eV, the electron density in the second flow already in 136 times exceeds the density of fast deuterons that ensure the neutron yield. Since the electron component in the plasma flows initially has a low temperature, but at the same time the velocity of electrons still exceeds the velocity of fast deuterons, then with increase of the density of „cold“ electrons there is increase of losses of energy of the fast deuterons for heating the electrons. It is well known and has been repeated noted. As an example, we can refer to the classic studies [52,53]. Keeping in mind this circumstance, it is mandatory to take into account the energy losses of the fast deuterons for heating the electrons when determining parameters of the deuterium plasma flows, at which there is the maximum value of the neutron yield. It is especially relevant for a collision of the flows with high energy content and, as a consequence, with a high plasma density in the colliding flows.

Let us carry out similar calculations for the case of collision of the deuterium plasma flow with the tritium plasma flow. Since the collision of the deuterium and tritium plasma flow has no symmetry due to a different mass of the deuteron and the triton, it is not unlikely that the above-considered variant of the same velocities of the flows is not optimal in terms of achieving the maximum neutron yield. We will find an energy ratio of deuterons and tritons in the laboratory system of coordinates, at which there is a local maximum of the D – T -neutron yield. For this, we transit in the neutron yield formula (11) from the energy of the deuteron in the system of coordinates, in which the tritium plasma flow is at rest, to the energies of the deuteron and the triton in the laboratory system of coordinates. As a result, we obtain the following formula for the D – T -neutron yield:

$$N_{dt} = \frac{6 \cdot 10^{-17} N_d N_t}{S(\sqrt{E_d} + 0.82\sqrt{E_t})^2 \left[1 + \frac{[(\sqrt{E_d} + 0.82\sqrt{E_t})^2 - 10^5]^2}{3 \cdot 10^{10}} \right]} \times e^{\frac{-1.5 \cdot 10^3}{(\sqrt{E_d} + 0.82\sqrt{E_t})}}. \quad (14)$$

Instead of the full number of deuterons and tritons we substitute its expression via the energy content of the flows and the energies of deuterons and tritons in the laboratory system of coordinates into the formula (14). Transiting to the energy content of the flows in Joules and taking into account that the energy content of the flows is the same and is W , we obtain the following formula for the D – T -neutron yield:

$$N_{dt} = \frac{2.34 \cdot 10^{21} W^2}{SE_d E_t (\sqrt{E_d} + 0.82\sqrt{E_t})^2 \left[1 + \frac{[(\sqrt{E_d} + 0.82\sqrt{E_t})^2 - 10^5]^2}{3 \cdot 10^{10}} \right]} \times e^{\frac{-1.5 \cdot 10^3}{(\sqrt{E_d} + 0.82\sqrt{E_t})}}, \quad (15)$$

where W is in [J], E_d and E_t in [eV], S in [cm²].

In the formula (15) we fix the value of the triton energy $E_t = 20.4$ keV, which corresponds to the velocity of triton motion in the laboratory system of coordinates, which is $1.14 \cdot 10^8$ cm/s. We vary the deuteron energy within the interval $E_d \leq 13.6$ keV and obtain the dependence of the $D-T$ -neutron yield on the deuteron energy at the said value of E_t . At the next step, we decrease the value of E_t and obtain a new curve of the dependence of the $D-T$ -neutron yield on E_d within the interval $E_d \leq 13.6$ keV. Thus, we obtain a family of the curves of the dependence of the neutron yield on E_d for the series of the values of E_t , which is shown in Fig. 4. By means of this family, we determine a point in space (E_t, E_d) , in which the $D-T$ -neutron yield has a maximum value within a region of the assumed limitations ($v_t, v_d \leq 1.14 \cdot 10^8$ cm/s).

It follows from the curves of Fig. 4 that within the interval of the values of E_d (0.7–13.6 keV) for all the values $E_t \leq 20.4$ keV there is observed monotonic increase of the $D-T$ -neutron yield with increase of E_d . The neutron yield gets a local maximum only on the curve that is constructed for $E_t = 26.9$ keV. This maximum is achieved when $E_d = 13.6$ keV and it is $2.09 \cdot 10^{14}$ $D-T$ -neutrons per pulse.

If we consider a behavior of the value of the neutron yield with decrease of E_d for the fixed value of E_t , then, as in the case of collision of the deuterium plasma flows,

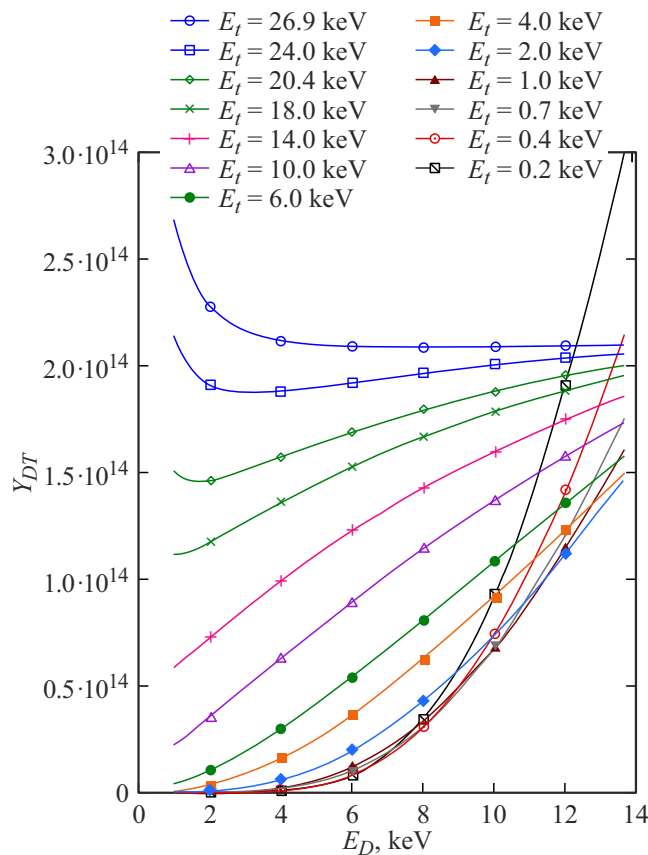


Figure 4. Curves of the dependence of the $D-T$ -neutron yield on the energy of the deuteron when $W = 160$ kJ.

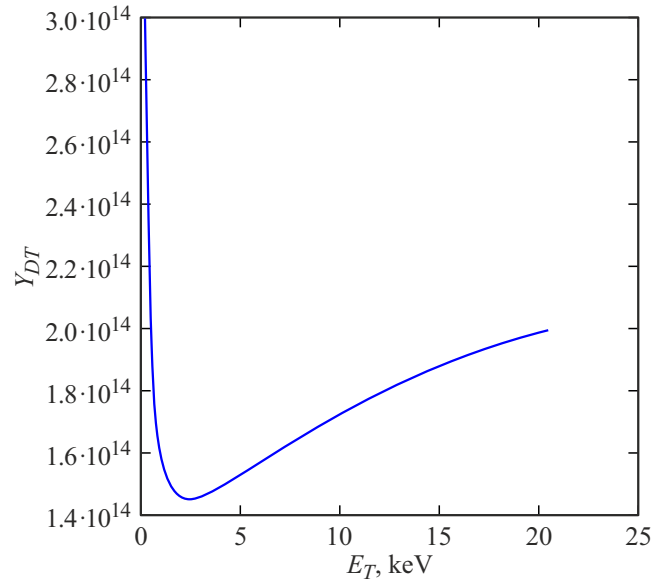


Figure 5. Dependence of the $D-T$ -neutron yield on the triton energy when $E_d = 13.6$ keV without taking into account the losses of energy of deuterons and tritons for heating the electrons.

first the value of the neutron yield decreases to achieve a certain minimum value. For the curve that corresponds to $E_t = 26.9$ keV, it is achieved when $E_t = 7.1$ keV to be $2.08 \cdot 10^{14}$ $D-T$ -neutrons per pulse and then it starts sharply increasing. For the curves that correspond to $E_t = 24.0, 20.4$ and 18 keV, the minimum value is achieved when $E_t = 3.3, 1.7, 1$ keV to be respectively $1.87 \cdot 10^{14}, 1.45 \cdot 10^{14}$ and $1.12 \cdot 10^{14}$ $D-T$ -neutrons per pulse.

As in the case of collision of the deuterium plasma flows, the minimum is caused by the fact that first with increase of the deuteron energy and respective increase of the their number a drop of the value of the reaction section prevails over increase of the number of deuterons. Then, with further decrease of the deuteron energy, increase of the number of deuterons has a stronger effect on the yield as compared to decrease of the value of σ_{DT} . If we consider the behavior of the $D-T$ -neutron yield when $E_d = 13.6$ keV and when varying the triton energy, a similar pattern is observed. As follows from the curve of Fig. 5, with decrease of E_t from 20.4 to 2.5 keV the $D-T$ -neutron yield decreases from $2 \cdot 10^{14}$ to $1.45 \cdot 10^{14}$ per pulse. Further decrease of the triton energy exhibits quite sharp increase of the neutron yield, which at $E_t = 0.2$ keV reaches the value of $3 \cdot 10^{14}$ $D-T$ -neutrons per pulse, which significantly exceeds the value of the neutron yield for the point ($E_t = 20/4$ keV, $E_d = 13/6$ keV). Explanation of this behavior of the value of the neutron yield is similar to the above one.

As noted above when analyzing the dependence of the neutron yield in collision of the deuterium plasma flows, based on such simple estimates it is impossible to conclude that at the values of the energy of the plasma streams, which are at least 50 kJ, variation of the deuteron or triton

energy can provide the neutron yields that are higher than those followed from the formula (15) when $E_t = 20.4$ keV and $E_d = 13.6$ keV. For this, the calculations require at least taking into account the losses of deuterons and tritons for heating the electron component.

Conclusion

We have developed a computational model of the neutron yield in flight of the two high-velocity deuterium plasma flows through each other as well as in flight of the deuterium plasma flow and the tritium plasma flow through each other and carried out the estimated calculations of this neutron yield.

As a result of the performed calculations, the following is found.

1) When the two deuterium plasma flows collide, whose velocity does not exceed $1/14 \cdot 10^8$ cm/s:

- the maximum neutron yield is achieved when the flows have the same velocities of $1/14 \cdot 10^8$ cm/s, the value of the neutron yield monotonically decreases with decrease of the velocity of the plasma flows;

- if we do not take into account the losses of the energy of deuterons for heating the electrons, then in order to achieve the values of the neutron yield 10^{12} D–D-, 10^{13} D–D- and 10^{14} D–D-neutrons per pulse, the energy content of each flow that has the cross-sectional area of 30 cm^2 shall be at least 160, 510 and 1600 kJ, respectively;

- with decrease of the velocity of the plasma flows from $1.14 \cdot 10^8$ to $8.8 \cdot 10^7$ cm/s the neutron yield decreases by no more than 50 % of its maximum value.

2) When the deuterium plasma flow collides with the tritium plasma flow, whose velocities do not exceed $1.15 \cdot 10^8$ cm/s:

- the maximum D–T-neutron yield is achieved when the flows have the same velocities of $1.15 \cdot 10^8$ cm/s, the value of the neutron yield monotonically decreases with decrease of the velocity of the plasma flows;

- when transiting from the collision of the deuterium plasma flows to the collision of the deuterium plasma flow with the tritium plasma flow, a value of the conversion factor is ~ 200 ;

- within the range of the values of the energy content of the flows from 160 to 1600 kJ, with decrease of the velocity of the flows from $1.15 \cdot 10^8$ to $0.9 \cdot 10^8$ cm/s the neutron yield decreases in no more than two times.

Taking into account the modern level of the technology of the pulsed plasma accelerators, it is quite realistic to create the pulsed synthesis neutron source with the yield 10^{13} – 10^{14} D–D ($2 \cdot 10^{15}$ – $2 \cdot 10^{16}$ D–T in conversion) neutrons per pulse.

Acknowledgments

We would like to thank V.P. Bakhtin, A.G. Es'kov, D.A. Toporkov and N.M. Umrikhin for many useful dis-

cussions and V.E. Cherkovets for continuous interest in the study.

Funding

The study is based on State Contracts № H.4k.241.09.22.1074, dated April 28, 2022 and № H.4k.241.09.24.1050, dated April 25, 2024.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by M. Shevelev