Neutron yield from Z-pinches at generation of the power-degree spectrum of fast deuterons

V V Vikhrev¹, A Yu Frolov² and A Yu Chirkov²,³

¹ NRC Kurchatov Institute, Ploshad Akademika Kurchatova, 1, Moscow, 123182 Russia
² Bauman Moscow State Technical University, Vtoraya Baumanskaya ul. 5/1, Moscow, 105005 Russia
³ E-mail: chirkov@bmstu.ru

Abstract. The neutron yield from the plasma of deuterium Z-pinch is analyzed with a power-law spectrum of fast deuterons in the energy range from several hundred keV to several MeV. The influence of the typical energies of fast deuterons and the exponent index of the spectrum is considered. The efficiency of neutron generation is estimated by the ratio of the neutron yield to the average deuteron energy. It was shown that when generating fast deuterons with energies of the order of 1 MeV, the reaction rate is much higher than for Maxwellian plasma with a temperature of the order of 10 keV.

1. Introduction
Studies of neutron generation in pinch discharges have a long history [1]. The first experiments on Z-pinches in the 50s of the 20th century demonstrated intense neutron radiation, which gave rise to great optimism. Further studies, as is known, showed the complex nature of the processes occurring in pinch discharges. Thus, neutron radiation is not associated with the achievement of high thermonuclear temperatures in the discharge plasma, but with high-energy ions accelerated during the development of MHD instability [2].

The high neutron yield allows consider pinch systems as sources of neutrons for various applications, but these systems in their current form are not suitable for the creation of a fusion reactor. The advantages of neutron sources based on pinch are their relative simplicity and compactness. The instability in the Z-pinch is an energy source for fast ions that initiate an intense fusion reaction. As shown by the analysis of the spectra of fast ions and neutrons, the ion energy distribution is very different from Maxwellian one. When ions are accelerated in the discharge, a spectrum is formed with a high-energy “tail”, falling approximately according to a power law [3]. This leads to some features of the characteristics of neutron radiation [4].

To evaluate the efficiency of neutron generation, it is necessary to adequately take into account the features of the fast-ion spectrum when calculating the rates of fusion reactions. The reaction rate in a thermonuclear deuterium plasma when heated by an external beam is significantly higher than for Maxwellian plasma [5], but the beam energy is also spent on heating the plasma [6]. Therefore, the energy output is several times less than the energy input [7]. The difference between pinch systems is that fast ions receive energy directly in the discharge, and due to the short duration of the process, they do not relax to Maxwellian distribution.
2. Fast deuterons in Z-pinch

The advantage of Z-pinch systems as a neutron source is no need for external drivers for plasma ion heating. In Z-pinch systems, developing magneto-hydrodynamic (MHD) instability is the source of energy for ions. The energy of the magnetic field of the pinch is firstly converted into thermal energy of the plasma, and then the resulting MHD instability forms fluxes of high-energy ions with a power-law energy distribution [2]. Such a distribution allows one to generate neutrons with the total yield over 10 times greater than the yield from Maxwellian plasma with corresponding temperature.

The process of gradual transition from the Maxwellian distribution of ions at the initial stage of Z-pinch compression to the power-law distribution with further heating of the pinch plasma by current are closely connected with the turbulence. The process of forming the power-low distribution is due to fast heating of ions, ion-ion Coulomb collisions do not Maxwellize ions. As a result, the state of high-temperature plasma at the maximum compression of the Z-pinch is characterized by a high content of high-energy ions which is comparable with the thermal population. Nuclear collisions of high-energy ions with relatively cold background plasma cause an increase in the neutron yield. At the final stage of the Z-pinch discharge temporally averaged particle energy distribution has the power-law form

\[
 f(E) = \frac{dN}{dE} = \frac{C}{E^k},
\]

where \( E \) is the ion energy, \( k \) is the power index, \( C \) is the normalization constant.

According to modeling the power index is in the range \( 2 < k < 4 \) [1]. The most probable energy distribution of particles, apparently, is the distribution with \( k \approx 2.7 \) [2]. Such a distribution is universal in the presence of strong turbulence.

Note that the power distribution is the result of averaging over a certain time interval. Therefore, the physics of such process is fundamentally different from the case of steady-state distribution in the beam-heated plasma [8–10].

In Z-pinch devices, fluxes of deuterons with energies up to 5 MeV are detected. In some studies, it is assumed that the appearance of these fast deuterons can be caused only by the acceleration in electromagnetic fields. However, there is no quantitative explanation of the spectra of high-energy deuterons based on such acceleration mechanisms. Another explanation of the high energy deuteron flux can be suggested on the basis of expansion of plasma with high average energy. The possibility of such an interpretation is related to the fact that deuterons with energy of ~ 5 MW have a Larmor radius comparable to the pinch radius. Such particles fly out of the compressed pinch area. Directed flow of high-energy deuterons from the chaotic velocity distribution is formed.

Normalized neutron yield (reactivity) due to reaction of fast ions with thermal ions of the background plasma is

\[
 Y = \int_{E_0}^{E_m} \sigma v f(E) dE,
\]

where \( \sigma \) is the cross section of the reaction, \( v \) is the fast ion velocity, \( E_m \) is the upper bound of the energy of fast ions (an order of 5 MeV), \( E_0 = (k + 1)T \) is the energy corresponding to the smooth conjugation of the high-energy tail of the distribution function with the Maxwellian part, \( T \) is the temperature of the background plasma.

In formula (2), the integration over time is transformed into integration over energy taking into account the temporal evolution of pinch parameters [1].

3. Neutron spectra

Figure 1 shows the results of calculating normalized neutron yield (reactivity) for the reaction of the deuterons of the power spectrum with the background plasma as a function of the average tail energy for various exponent indexes. For comparison, the neutron yield for Maxwellian plasma is also shown.
Fast deuterons take energy from compressing magnetic field of the pinch. Compression of the magnetic field also leads to plasma heating. To analyze the efficiency of the conversion of this energy, one can consider the ratio of the neutron yield (reactivity) to the average ion energy

\[ R = \frac{Y}{<E>} \tag{3} \]

The results of the calculation of this quantity are shown in figure 2. As can be seen, for different values of the tail exponent index, the efficiency of neutron generation due to reactions of fast deuterons with energies of the order of 1 MeV exceeds the generation efficiency in Maxwellian plasma with a similar or lower level of average ion energy.

**Figure 1.** Normalized neutron yield (reactivity) for the reaction of deuterons of the power spectrum with the background plasma depending on the average tail energy (solid lines 1–4) and reactivity for Maxwellian plasma (dashed line 5). Exponent indexes: \(1 – k = 1, 2 – 2, 3 – 2.7, 4 – 3\).

**Figure 2.** The ratio of the neutron yield (reactivity) to the average ion energy for the power distribution (solid lines 1–4) and Maxwellian plasma (dashed line 5). Exponent indexes: \(1 – k = 1, 2 – 2, 3 – 2.7, 4 – 3\).
Figure 3. The ratio of reaction rate for a plasma with a power-law spectrum of fast deuterons to the rate for Maxwellian plasma.

Figure 3 shows the ratio $Y_{\text{pow}}/Y_{\text{Maxwell}}$ of reaction rate for the case of fast deuterons with a typical power spectrum ($k = 2.7$) to the reaction rate for Maxwellian plasma with temperature $T$. The maximum energy is assumed $E_m = 100T$. In this case, the average energy of high-energy deuterons is $<E> \approx 10T$, the average energy over the total energy distribution is $<E> \approx 2T$.

4. Conclusions

It is shown that the efficiency of the generation of fast deuterons with energies of the order of 1 MeV is much higher than for Maxwellian plasma with a temperature of the order of 10 keV. An important feature of the Z-pinches is the conversion of the energy of instability into the energy of fluxes of high-energy particles. Therefore, Z-pinches can be considered as promising devices for the generation of fast neutrons for various applications. The efficiency of neutron generation, apparently, can be increased as a result of optimization.

References

[1] Vikhrev V V, Korolev V D 2007 Plasma Physics Reports 33 356
[2] Vlasov V P, Zhdanov S K, Trubnikov B A 1989 JETP Letters 49 667
[3] Vikhrev V V, Mironenko-Marenkov A D 2012 Plasma Physics Reports 38 225
[4] Vikhrev V V, Baronova E O, Dodulad E I, Frolov A Yu 2019 46th Int. Zvenigorod Conf. Plasma Phys. and Contr. Fusion. http://www.fpl.gpi.ru/Zvenigorod/XLVI/It/en/EE-Baronova_e.docx
[5] Chirkov A Yu, Vesnin V R, Dolganov V V 2016 Prikladnaya Fizika 2 5
[6] Vesnin V R, Chirkov A Yu 2018 Problems of Atomic Science and Technology. Ser. Thermonuclear Fusion 41 (2) 34
[7] Chirkov A Yu, Vesnin V R 2018 Journal of Physics: Conf. Series 1094 012019
[8] Chirkov A Yu 2015 Nucl. Fusion 55 113027
[9] Almagambetov A N, Chirkov A Yu 2016 Journal of Fusion Energy 35 845
[10] Chirkov A Yu, Vesnin V R 2017 Journal of Physics: Conf. Series 891 012306