Mechanisms for neutron generation in Z-pinches

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Abstract. The studies of neutron emission in Z-pinches are analyzed in this work. The available ideas concerning the nature of neutron emission are contradictory. The terms “fusion mechanism” and “acceleration mechanism” used in publications concerning neutron generation are unable to explain all characteristic properties of Z-pinches observed experimentally. The physical grounds for using these mechanisms are also not fully confirmed. The revision of the existing theoretical approaches makes it possible to reveal new methods for studying Z-pinches, such as the studies of considerable energy release in the Z-pinch plasmas due to the development of MHD instability, as well as the studies of the energy transport during which the most of the magnetic field energy is transported directly to ions, without the participation of the electron component.

1. Introduction

The research in the field of the high-current discharges or Z-pinches is a part of the general problem of obtaining controlled fusion (CF) reactions. This research lasts for more than half a century. However, the prospects of Z-pinches are still not clear. To clear up these prospects, we will begin with the history of discovering neutron emission in Z-pinches.

In 1952, neutron emission from the pulsed discharges in deuterium was recorded at the Kurchatov Institute of Atomic Energy. The gas-discharge chamber was a cylinder with the dielectric lateral surface and conductive electrodes connected to the energy source through the gas-filled gap. When the current with the amplitude of the order of hundreds of kiloampères flowed in such a facility, the burst of neutrons was observed [1].

Intense neutron emission lasted for a fraction of a microsecond. Such short duration was attributed to the magnetohydrodynamic (MHD) instability developing in the discharges and plasma cooling on the electrodes [2]. In order to increase the generation time, the attempts were made to suppress the instability and reduce the plasma interaction with the chamber electrodes. For this purpose, the stabilizing magnetic field was imposed and the discharge was "curved" into a torus. Thus, the electrodeless configuration was created, which, along with the magnetic field applied to the discharge, is called now the tokamak (toroidal chamber with magnetic coils).

We note that the desire to increase the generation time stems from the desire to create the stationary operating fusion reactor. Today, the creation of the international fusion reactor ITER grounds on the results achieved at tokamaks. Nevertheless, in the Z-pinches, the neutron yield per expended energy is still higher. It turned out that the reason for this is associated with the fact that the magnetic field energy is transported to the ion component of the pinch plasma.
2. Neutrons from Z-pinches

In [2], L. A. Artsimovich summarized the results of research in the field of Z-pinches and indicated that until “now” (i.e., until 1960), it has not yet been possible to create conditions, under which neutron emission would occur as a result of only fusion reactions. At that time, nuclear reactions that occur at low energies of interacting particles were called “non-fusion” reactions (for example, fission reactions of heavy nuclei occurring when they interact with thermal neutrons).

It has now been ascertained that in the Z-pinches, neutron emission is the result of nuclear interaction between plasma ions occurring due to their high relative velocities. No other phenomena responsible for the generation of neutrons have been found. In this sense, neutrons generated in the high-current deuterium discharges are produced only as a result of the DD fusion reaction.

However, the terms "fusion" and "non-fusion" did not disappear, but changed their appliance to the physical phenomenon. Moreover, they are applied not only in the field of gas discharge research. Initially, the term "fusion" meant the nuclear fusion reaction, but later it meant the mechanism for neutron generation in plasma. So, if the energy distribution of deuterons in plasma is close to the Maxwellian one, then we will speak about the fusion mechanism for neutron generation, and otherwise, this mechanism will be the acceleration mechanism.

Thus, the calculations of the neutron generation intensity can be performed in two very different ways:

- In one method, the presence of a thermal distribution of particles is assumed (Figure 1). Such a distribution forms when the plasma lifetime is considerably long, as compared to the time of its thermalization (the time of ion-ion interactions). In this case, the generation mechanism was called the fusion mechanism.
- In the second method, the presence of a double-humped particle distribution is assumed (Figure 2). It forms, for example, when the beam of accelerated ions is injected into the plasma of the stationary reactor [3]. The mechanism for neutron generation due to the interaction of high-energy ions with low-energy ions was called the acceleration mechanism.

In any case, to calculate the neutron yield, it is necessary to know the true space and time distributions of ions. It is often difficult to know them. Therefore, you have to use one of the above calculation methods, assuming the thermal distribution (Figure 1) or the double-humped distribution (Figure 2).

![Figure 1. The Maxwellian distribution of ions in plasma.](image1)

![Figure 2. Double-humped distribution of ions in plasma. Left hump corresponds to the Maxwellian distribution with the characteristic energy much less than the characteristic energy of the distribution close to the monoenergetic one (right hump).](image2)

When we deal with the acceleration mechanism, neutrons are generated due to the interaction of the beam of moving ions with a certain target. Therefore, this mechanism is also called the target
mechanism. The acceleration of ions occurs due to the action of external forces. Assuming that the ion energy in the beam considerably exceeds the energy of the target ion at rest, the neutron generation rate can be determined from the following relation:

\[ Y \sim n_u n \cdot \sigma(E_0) \cdot v \]  

(1)

where \( n \) is the density of target ions, \( n_u \) is the density of accelerated ions, \( \sigma \) is the cross section of nuclear fusion reaction, \( v \) is the velocity of accelerated ions, and \( E_0 \) is the energy of accelerated ions.

In the framework of the fusion mechanism, the reaction rate is determined by the plasma temperature. The work of external forces is spent on increasing the average plasma energy, but not on accelerating the individual ions. In this case, the energy distribution tends to be the Maxwellian one and the neutron generation rate is determined by the following expression:

\[ Y \sim n^2 \cdot \left\langle \sigma v \right\rangle_T \]  

(2)

where \( n \) is the plasma ion density, and \( \left\langle \sigma v \right\rangle_T \) is the fusion reaction rate for plasma with the temperature \( T \).

Comparison of these two mechanisms shows that for the fusion mechanism, the rate of neutron generation is proportional to the square of the plasma density, in contrast to the acceleration mechanism, where it is simply proportional to the ion density of the beam. Therefore, the acceleration mechanism for neutron generation is considered to be less promising in terms of achieving ignition of fusion reactions. At energies of approximately 6–8 keV, for DD or DT plasmas, the reaction rate for the mono-energy beam interacting with the target becomes comparable to the reaction rate for the Maxwellian plasma [2].

If the neutron yield is calculated as a sum of the yields provided by both mechanisms, then all ions in the plasma should be formally quantitatively divided into two groups. The first group consists of the accelerated ions, which form the beam and, when interacting with the target, produce neutrons in accordance with the acceleration mechanism. The second group consists of the target ions, which, when interacting with each other, produce neutrons in accordance with the fusion mechanism.

In the Z-pinches, the neutron yield provided by both mechanisms is often calculated [4]. In this case, it is assumed that their contributions are approximately equal. Of course, the use of these mechanisms is justified in the framework of the accepted concepts of the Z-pinch physics. However, the resulting contradictions between theory and experiment impeach the correctness of the assumptions made.

3. Acceleration mechanism

The involvement of the acceleration mechanism to explain neutron emission in the Z-pinches is based on the following prerequisites. The neutron yield obtained in experiments cannot be explained, if the energy distribution of ions is the purely Maxwellian one. Therefore, it was assumed that in the final stage of the Z-pinch development, the strong electric field directed along the axis of the discharge forms at the waist [5]. This field accelerates some part of the ions, which, interacting with non-accelerated ions, produce the missing neutrons.

The use of the acceleration mechanism implies the presence of a double-humped ion energy distribution (Figure 2), which can be considered as a superposition of the Maxwellian and monoenergetic distributions. The scattering of two kinds of ions by each other is often neglected. At the same time, the distributions of both kinds of ions do not change in time. For the Maxwellian distribution, such dynamics is typical, in contrast to the monoenergetic distribution, which also tends to be thermalized. Preservation of the direction of the beam motion is consistent with the absence of interaction between the accelerated and target ions. As for the electric field, it is assumed that it acts only on the accelerated ions. The target ions remain motionless on average.
The combination of these two mechanisms gives the neutron yield comparable to that obtained in the experiment. However, there occur several contradictory consequences associated with the joint use of these mechanisms.

In the framework of the acceleration mechanism, it is not clear what fraction of ions is accelerated. Usually, electrons are the carriers of the electric current in conductors. The ratio of the ion to electron currents in plasma can be estimated by comparing their masses $m_i/m_e$. For example, for deuterium, this ratio is equal to $\approx 1/3700$, or $\approx 0.027\%$. The acceleration of ions should be considered taking into account the fact that the electron component present in plasma is more susceptible to the electric field action than the ion component. In [4], to explain the neutron yield measured in the Z-pinches, it is assumed that ions carry approximately ten percent of the total current.

The anisotropy of energy is typical of the neutron emission of Z-pinches [6]. The full width at half maximum of the experimental spectra recorded in different directions varies from tens to hundreds of keV. If we assume the Maxwellian distribution of ions, the spectral width will characterize the ion temperature [7]. In the framework of the acceleration mechanism, the distribution of the accelerated ions in the waist is assumed to be monoenergetic. The width of the spectrum of neutrons generated in the direction perpendicular to the pinch axis should tend to zero [4].

Ions with energies of the order of several MeVs were detected in the Z-pinches [8, 9]. In the framework of the acceleration mechanism, the ions can acquire such energies, if the potential differences of the order of $10^9$ V are present in the discharge. However, the available experimental data on the voltages in the chambers of the plasma focus facilities do not confirm this assumption [10].

It was found that the spectrum of ions escaping from the waist is neither Maxwellian, nor monoenergetic [11]. At high energies, it can be described by a power function of the following form:

$$\alpha_c(E) \sim E^{-k}$$  \(3\)

where $k = 2 \div 3$ is the exponent.

It is a separate problem to find out how the spectrum of emitted ions correlates with the real plasma distribution inside the contracting waist. The neutron yield calculated under the assumption of power-series distribution of ions (3) is higher as compared to that for the Maxwellian distribution, the average ion energies being equal [12].

On balance, the use of the acceleration mechanism to explain the generation of neutrons leads to the results that contradict experiments and existing plasma concepts:

- the fraction of the ion current in the Z-pinch is overestimated as compared to the fraction of the electron current;
- the widths of the spectra of generated neutrons measured in different directions should considerably differ;
- to accelerate ions in the electric field to energies of the order of several MeVs, in the final stage of Z-pinch development, the voltages should be of the order of $10^8 \div 10^9$ V;
- the double-humped distribution of ions (Figure 2) inside the waist corresponds to the power law spectrum of ions (3).

4. Fusion Mechanism

Neutron emission based on the fusion mechanism is associated with the high internal energy of plasma and, presumably, short time of plasma thermalization, as compared to the times of variation of the Z-pinch characteristics. This assumption is acceptable till the contribution of the processes potentially changing the ion distribution is much less than the contribution of the maxwellization process, characterized by the frequency of ion-ion interactions:

$$V_i \equiv 10^{-6} \cdot \frac{n \text{[sm}^{-3}\text{]}}{T^{3/2} \text{[eV]}}$$  \(4\)
For densities of $n \sim 10^{19} \text{ cm}^{-3}$ typical of the Z-pinches and temperatures of $\sim 1 \text{ keV}$, this frequency is of the order of $10^{-9} \text{ s}^{-1}$. If we assume that after several ion-ion interactions, the Maxwellian distribution is established, then the thermalization time will be several nanoseconds.

The fusion mechanism explains the width of the spectrum of generated neutrons. In the radial direction, this width can characterize the ion temperature in the waist.

In the framework of the fusion mechanism, neutron emission is associated with the immobility of the generation region. In other words, the central system of coordinates (C-system) of the target plasma coincides with the laboratory system of coordinates (L-system). Such emission should be isotropic. However, the observed anisotropy can be explained by the mobility of the neutron generation region.

The dynamics of the current-plasma sheath (CPS) is characterized by the increased radial velocity of motion near the anode, which occurs due to the Hall effect [13]. Due to this fact, there arise the prerequisites for "forcing away" the region of compressed plasma from the anode towards the cathode with the velocity of the order of the hydrodynamic velocity of the CPS motion. In addition to the motion of the C-system associated with the region of neutron generation relative to the L-system, the Hall effect creates the preconditions for the isotropy violation of the ion motion in the waist region due to the conical shape of the CPS [14]. This was especially clear observed in experiments [6], in which not only the energy anisotropy of neutron emission was revealed, but also the quantitative anisotropy. This effect requires the additional research, since the hydrodynamic velocity of the axial motion of the neutron emission region is of the order of $10^7\sim10^8 \text{ cm}/\text{s}$, and to obtain neutrons with the maximum energy of 2.8–3.0 MeV moving towards the cathode, they should be of the order of $10^8\sim10^9 \text{ cm}/\text{s}$.

In the framework of the acceleration mechanism, the formation of the double-humped distribution is complicated by the fact that initially, the energy of accelerated ions is comparable to the average energy of all ions, and their distribution has the Maxwellian shape. With allowance for the fact that the frequency of ion-ion interactions decreases with increasing ion energy, the acceleration mechanism should result in the appearance of the high-energy tail rather than the double-humped distribution. The power-law shape of the spectrum can be explained by the development of instability. When plasma is compressed, its temperature and density considerably change in time. And since the experimental spectrum is recorded during the finite time, we can assume that this spectrum is a certain integral of the instantaneous energy distributions in the waist, multiplied by the velocity of escaping ions:

$$ F(E) = \int_{E_i}^{E_f} f(E) \cdot \left( -\frac{dN}{dt} \right) \cdot dt, \quad (5) $$

where $f(E)$ is the instantaneous ion distribution in the waist, and $N$ is the number of ions in the waist. In the case of the Maxwellian $f(E)$ distribution, the final spectrum should have the upper energy edge, as it is in power law (3). However, such a spectrum edge was not found experimentally. This can be explained by the fact that the ion temperature in the waist is higher than that measured experimentally, or the ion energy distribution in the waist changes in the course of the waist contraction.

The fusion mechanism for neutron emission is not the reason for reaching the extreme values of physical parameters in the Z-pinches. But at the same time, in the framework of this mechanism, it is impossible to explain all the facts experimentally observed. The following issues still remain unclear:

- high energies of ions escaping from the waist;
- neutron emission anisotropy: spectra measured in different directions have their own characteristic spectral widths;
- power law shape (3) of the spectrum of ions escaping from the waist.

On the whole, the applicability of the fusion mechanism looks reasonable. However, due to the presence of strong instability, the conditions may arise, under which the fusion mechanism should be somehow modified. Namely, it is necessary to take into account the mobility of the C-system relative
to the L-system and the possibility of deviating the ion distribution in the waist from the Maxwellian distribution.

5. Conclusions
Considering two mechanisms for neutron generation in plasma (acceleration and fusion ones), we can conclude that the available experimental data on the Z-pinches are poorly interpreted by the existing theory. Within the framework of the acceleration mechanism, in order to explain the neutron generation, we should assume the extreme values of physical parameters. Within the framework of the acceleration mechanism, it is impossible to explain all observed characteristic properties of the Z-pinches. Thus, in order to construct the full theoretical model of the Z-pinch, we should revise the existing approaches. We should cast doubt upon the reasonability of using the acceleration mechanism. The fusion mechanism should be improved and its domain of applicability should be analyzed.

To construct the complete physical picture of the Z-pinch, it is necessary to interrelate all of its characteristic properties observed experimentally, namely, the anisotropy of neutron emission, the width of the neutron emission spectrum, the shape of the spectrum of ions escaping from the waist, the increased neutron yield, and some others. Special attention should be paid to studying the mechanisms responsible for the energy transport from the magnetic field directly to the ions and capable of changing the shape of their distribution in the waist. Apparently, these mechanisms are associated with the instability actively developing in the Z-pinches.

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