Neutron emission in big tokamaks

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Possible mechanisms of neutron emission in large tokamaks are discussed. It is shown that the observed neutron yields agree well with the calculated value under normal operating conditions of the T-10 installation. The anomalous neutron emission, which reaches 10^{12}–10^{13} neutrons per discharge, is attributed to a photonuclear reaction on the diaphragm. Estimates of the current of the relativistic electron beam under conditions are presented. The anomalous behavior of the neutron intensity in individual discharges is attributed to electrodisintegration of the plasma deuterium.

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1. INTRODUCTION

Probably none of the physical phenomena accompanying the production of hot plasma in devices constructed as part of the program of controlled thermonuclear fusion (CNF) has attracted as much interest as the neutron emission from a deuterium plasma. This is not surprising, since the entire idea and purpose of the CNF program is to reach temperatures, densities, and lifetimes such that nuclear reactions of sufficient intensity are initiated in the plasma, particularly reactions in which neutrons are produced. It seemed that measurement of the neutron flux, which is easy to detect and to estimate quantitatively, would be a splendid, reliable and accurate, plasma ion thermometer. This conclusion, unfortunately, is in error and the neutron-emission pulses repeatedly observed during the last quarter century in a great variety of installations and under various situations have been incorrectly interpreted and were bitterly disappointing. To substantiate this statement, we cite only a few examples. In 1952, only two years after the start of the thermonuclear program, neutrons were registered in our country and in the USA with systems of the *Z*-pinch type; in 1957, neutron emission was observed in England with the "Zeta" toroidal installation with weak longitudinal field; a few year later, in 1961, open-trap neutrons were detected in the USA. In all the foregoing cases the observed emission had no bearing whatever on the plasma heating. Equally doubtful was the nature of the neutron emission in the early experiments with Θ pinches, plasma focus, and the first experiments with laser heating of microtargets.

Years have passed, and the use of more and more sophisticated diagnostic methods (detailed investigations of the energy spectrum of the neutron emission, analysis of the evolution of the emission in time, study of the spatial distribution of the neutron-flux intensity, and others) have enabled physicists to differentiate reliably between "true" thermonuclear emission and side effects. This does not mean, however, that in all cases, without exception, the mechanism of the observed neutron pulses could be explained. As a rule, the observed neutrons of non-thermonuclear origin were ascribed to the group of fast deuteron interacting with the target from the cold plasma, but the question of the origin of the fast deuterons was frequently debatable.

It is curious that the more complicated and powerful the thermonuclear installation became and the better the understanding of the processes, the larger the number of possible mechanisms capable of causing the neutron emission has become. The present paper is devoted to a discussion of the situation which has by now developed in the case of large tokamaks—toroidal systems with strong magnetic fields.

The experimental facts considered below were obtained with the T-10 installations, whose parameters and operating conditions were recently discussed in due detail.[1,2] We must note from the very outset that in the first cycle of the experiments performed with the T-10 there was no special program aimed at analyzing the extraneous neutron effects. This explains the somewhat fragmentary character of the exposition that follows.

2. POSSIBLE NEUTRON-EMISSION MECHANISMS

Three elementary processes can be responsible for the appearance of neutron emission in tokamaks and other thermonuclear installations of the closed type with magnetic thermal insulation: 1) deuteron collisions, 2) photonuclear reactions, and 3) electrodisintegration of the nuclei. The first process is realized in a deuterium plasma at high temperatures, in which case we say that thermonuclear reactions take place. However, as already mentioned, neutron emission can occur also in a cold plasma in the presence of a group of "detached" fast deuterons.

The secondary process is observed when runaway electrons appear in the plasma pinch and form, in the so-called accelerator regimes, beams of relativistic electrons. When electrons of energy $\gtrsim 8$ MeV are stopped by a massive solid target, the resultant x-ray photons cause photodisintegration of the nuclei of the target itself or of the nuclei of the gas in the chamber of the apparatus (provided, of course, that the latter is not hydrogen).

The third process is direct electrodisintegration of nuclei by a beam of electrons of sufficient velocity. It is again necessary to distinguish between two variants of the process. If $\varepsilon > 2.2$ MeV and the gas filling the chamber is deuterium, deuteron electrodisintegration takes place. If the electron energy begins to exceed the binding energy of the nucleons in the nuclei of the metallic targets, then electrodisintegration of the nuclei of the diaphragm material or of the linear material becomes possible.

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Let us estimate the intensity of the neutron emission and discuss its evolution in time for all three discussed variants.

The distinguishing features of thermonuclear reactions in a plasma are well known and will not be repeated here. We recall only that the reaction has no threshold, the emitted neutrons have spatial symmetry, the neutron energy is independent of the emission direction, and the half-width of the neutron energy distribution function is connected with T_i. The neutron emission was calculated for the T-10 setup by Dnestrovskiĭ and Lysenko[3] and lies in the range 10^9–10^{10} neutrons/pulse at typical values of the plasma current and density, and its time evolution duplicates the variation of n_i and T_i with time. The calculation results will be compared with the experimental data in the next section.

If the "deuteron beam–target" model is valid, there is no longer a unique connection between the neutron yield and the plasma current. The energy spectrum of the reaction products turns out to be spatially asymmetric (see, e.g.,[4,5]).

The photodisintegration of heavy nuclei in the 10–20 MeV region is characterized by a "giant resonance," a phenomenon wherein the nuclei are polarized and an electric dipole is induced. The reaction proceeds via a compound nucleus, so that the neutron emission is isotropic. The effective cross section of the reaction has a broad maximum—its half-width is ~6 MeV. The position of the maximum is determined by the approximate relation

$$\varepsilon_{max} \cong 80\,A^{-1/3}, \qquad (1)$$

where ε_{max} is the energy corresponding to the maximum and A is the mass number of the target nuclei. The cross sections increase relatively steeply past the threshold, and their dependence on the electron energy, for the two metals of interest to us—molybdenum and tungsten (of natural isotropic composition)—is shown in Fig. 1.[6,7,8] For deuterium, the threshold of the reaction is 2.2 MeV, the maximum of the cross section is observed at 4.4 MeV, and $(\sigma_{\gamma,n})_{max}$ is 2.4 mb.[9]

An appreciable fraction of the energy of a relativistic electron covering its mean free path in the target (several millimeters at $\varepsilon = 10$–15 MeV and $Z = 60$–80) is transformed into bremsstrahlung. The bremsstrahlung efficiency in a thick target is estimated from the known formula

$$\eta_0 = Q_\gamma / Q_e \cong 5 \cdot 10^{-4}\, Z\varepsilon. \qquad (2)$$

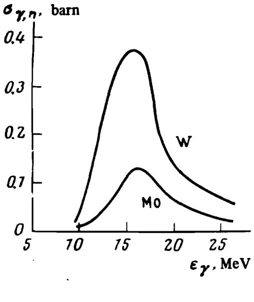

FIG. 1. Dependence of the cross section of the (γ, n) reaction on the γ-quantum energy for tungsten and molybdenum.

The electron energy is given here in MeV; the formula is valid up to ~20 MeV. The share of the hardest radiation is approximately one-quarter the total energy of the x-ray flux (as before, we refer to heavy nuclei and energies 10–20 MeV). The efficiency of the electron–hard photon process thus takes the form

$$\eta = {}^1/_4\,\eta_0 = N_\gamma / N_e \cong 10^{-4}\, Z\varepsilon, \qquad (3)$$

where N_γ is the number of hard photons produced in the targets, and N_e is the total number of relativistic electrons incident on the target surface.

To estimate the intensity of the neutron emission produced in the course of the (γ, n) reactions, it is necessary to examine the subsequent fate of the x-ray photons. At a target thickness 10–20 mm, the greater part of the hard photon passes through the targets and propagates subsequently in the form of a relatively narrow cone in the direction of the primary electron beam. The photons absorbed or scattered inside the target lose most of their energy to the Compton effect or pair production, and a small percentage causes photodisintegration of nuclei. We denote by n_a the number of target atoms per cm^3 and by N_γ the total number of hard x-ray photons produced in the targets or, more accurately, the number of photons with energy above the reaction threshold. The number of neutrons produced in a target of thickness l is then

$$R_{\gamma,n} = \sigma_{\gamma,n}(\varepsilon)\, n_a N_\gamma l. \qquad (4)$$

Using (3) and some obvious transformations, we get

$$R_{\gamma,n} = \eta \frac{N_0 \rho}{ceA} \sigma_{\gamma,n}(\varepsilon)\, L l I_e. \qquad (5)$$

Here I_e is the current strength in the relativistic electron beam, L is the total length of the plasma turn, ρ is the target density, N_0 is Avogadro's number, and e is the electron charge. Substituting the numerical values of the universal constants, assuming $\eta = 0.1$, i.e., $Z \cong 60$–80 and $\varepsilon = 12$–15 MeV, as well as a turn length $L = 10^3$ for the T-10 tokamak, we obtain

$$R_{\gamma,n} \cong 10^7 l \frac{\rho}{A} \sigma_{\gamma,n}(\varepsilon) I_e. \qquad (6)$$

Here $\sigma_{\gamma,n}(\varepsilon)$ is in millibarns. We note that at very high energies, $30 < \varepsilon < 300$ MeV, we can use the simple formula

$$R_{\gamma,n} \cong 1.5 \cdot 10^{-4}\, \varepsilon N_e, \qquad (7)$$

where ε is the particle energy in MeV, and N_e is the number of accelerated electrons. For the particular case of T-10, this relation becomes

$$R_{\gamma,n} \cong 3 \cdot 10^7\, \varepsilon I_e. \qquad (8)$$

Of course, photodisintegration under the influence of hard photons emitted from a massive target will take place also in a deuterium plasma, but since the plasma density is lower by about 10 orders than the target density, we can ignore this effect.

We turn now to the analysis of the time sequence of the events in the considered variant of the neutron production process. Assume that the Dreicer condition is satisfied for a certain group of plasma electrons. Then the produced detached electrons begin to acquire energy in the vortical electric field, and move approximately along the force lines B over the magnetic surfaces, or more accurately over the drift surfaces. The radial coordinate of the accelerating electron in a section through the plasma pinch will increase with time both on account of the drift of the individual trajectory and as a result of the expansion of the plasma pinch as a whole.[11] The acceleration process stops when the beam electrons start to reach the restricting diaphragm. The larger the permissible radial displacement of the electron trajectory, the longer, other conditions being equal, the acceleration process and the higher the final energy of the electron.

The connection between the reached energy and the acceleration time in the free-acceleration model in a vortical electric field is obtained from simple relations. We introduce the following notation: $U(t)$ is the plasma-pinch circuit voltage, L is the length of the torus, and p is the relativistic electron momentum. We can then write down the following obvious equations:

$$\dot{p}=eE(t)=eU(t)/L, \tag{9}$$

or, denoting the acceleration time by τ and the rest energy by ε_0, we get

$$p=\frac{1}{c}(\varepsilon^2-\varepsilon_0^2)^{1/2}=\frac{e}{L}\int\limits_0^\tau U(t)\,dt. \tag{10}$$

In the case $\varepsilon \gg \varepsilon_0$ of direct interest to us we have

$$\varepsilon\cong\frac{ec}{L}\int\limits_0^\tau U(t)\,dt. \tag{11}$$

If the circuit voltage remains practically constant during the acceleration, this equation takes the form

$$\varepsilon=\frac{ec}{L}U_0\tau. \tag{12}$$

For the T-10 setup, after substituting the numerical values of the constants, we can rewrite (12) in the form

$$\varepsilon\cong 32U_0\tau. \tag{13}$$

Here ε is in MeV and U_0 in volts.

Thus, the neutron emission due to photodisintegration of the target nuclei (i.e., the nuclei of the constricting-diaphragm material) should be observed in synchronism with the flash of hard x radiation and should be linearly related to the current in the electron beam [formula (6)]. It depends on the starting point of the group of detached electrons and a certain time is required for the accelerated beam to develop (formulas (12) and (13)). Of course, the effect will be observed regardless of whether the discharge chamber is filled with hydrogen or deuterium.

Let us discuss briefly the third neutron-production mechanism. If the discharge is in deuterium, the conditions for the formation of the accelerated beam are satisfied, and the electron energy begins to exceed 2.2 MeV, then electrodisintegration of the plasma deuterons becomes possible. We introduce the notation: n_e is the density of the electrons that pass through, n_d is the density of the deuterons in the plasma, and $\sigma_{e,n}(\varepsilon)$ is the effective cross section for the disintegration of a deuteron by an electron having an energy ε. The number of reactions per second and per cm^3 of plasma is then given by

$$(R_{e,n})_1=n_e n_d \sigma_{e,n}(\varepsilon)c. \tag{14}$$

In the entire volume of the torus, within a time τ and at an electron-beam current $I_e=jS$ (j is the current density and S is the beam cross-section area), the total number of events is

$$R_{e,n}=(R_{e,n})_1 V\tau=\sigma_{e,n}(\varepsilon)n_d\frac{I_e}{e}L\tau. \tag{15}$$

The neutron emission is accompanied by bremsstrahlung while some of the beam electrons are incident on the diaphragm, and the duration of the neutron pulse should coincide with the lifetime of the electron beam (at $\varepsilon > 2.2$ MeV).

If the relativistic-beam electron energy begins to exceed 7–8 MeV, then electrodisintegration of the massive-target nucleus becomes possible. But the cross sections for electron interaction with the nuclei is approximately one-hundredth the cross section for the interaction with the bremsstrahlung photons, and this phenomenon is inevitably masked by the powerful process of the photodisintegration of the target nuclei.

3. EXPERIMENTAL FACTS AND DISCUSSION OF THE RESULTS

At the end of the 1976 program of experiments with the T-10 setup, a series of runs was made in which the principal parameters of the discharge were maintained strictly constant. The longitudinal magnetic field (35 kG), the current in the plasma turn (400 kA), and the initial deuterium pressure (4×10^{-4} Torr) were "frozen." The average electron density in these discharges was is the range $\bar{n}_e=(4-6)\times10^{13}$ cm^{-3}. The chamber conditioning regime was also maintained constant.

Out of a total of about 300 pulses of this series, we registered in 260 cases the so-called normal discharges, characterized by the absence of any singularities whatever in the macroscopic parameters of the plasma pinch. Discharges with breaks in the current and with an abrupt increase of the torus circuit voltage were observed in 30 cases. At the instant of the current break, a flash of hard x-ray and neutron emission was produced; the neutron dose per discharge was anomalously large and reached 10^{10}–10^{11} neutrons. In the same series, 10 discharges were accompanied by development of sharply pronounced acceleration processes; their neutron yield exceed 10^{12} and the current oscillogram showed as a rule a characteristic "step."

In normal regimes, the neutron emission was regularly reproducible from experiment to experiment, and the

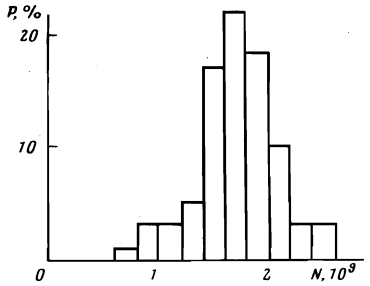

FIG. 2. Fraction P of discharge pulses with neutron yield N as a function of the neutron yield.

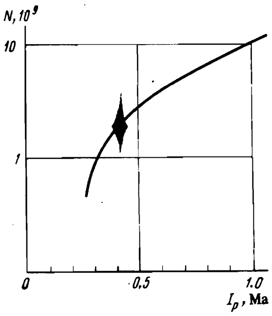

FIG. 4. Calculated dependence of neutron dose per T-10 pulse (solid curve) and experimental data.

histogram of Fig. 2 demonstrates clearly the high stability of the emission. The average neutron yield under the investigated conditions was 1.8×10^9 neutrons/pulse. The time dependences of the neutron and hard x-ray emissions in one of the typical discharges of the considered series are shown in Fig. 3. This figure shows also synchronized discharge current and voltage oscillograms and an oscillogram of the plasma-pinch displacement. As already noted, the dependence of the expected intensity of the neutron emission of thermonuclear origin on the current was calculated, for the given parameter, prior to the start of the experiments.[3] The corresponding plot is shown in Fig. 4 together with the experimental data. We see that the agreement between the preliminary calculation and the observations is good.[1)]

The illustrations presented need apparently no more commentary, except that the displacement on the oscillogram of Fig. 3c corresponds to broadening of the plasma pinch along the major radius. A displacement having this sign is registered without exception on all oscillograms corresponding to the normal regimes. The range of the radial displacements, within which the electron-acceleration process can evolve under these conditions, is quite narrow.

Figure 5 shows oscillograms for one of the acceleration discharges (4×10^{12} neutrons per discharge). As expected, the neutron radiation correlates most rigorously with the hard x-ray flash. At the instant of the current break, when the equilibrium along the major radius of the torus is lost, the plasma pinch moves sharply towards the interior immediately before the start of the x-ray and neutron emission. On the torus circuit, at the same time, an inductive voltage component is produced, and a swift expansion of the plasma pinch is observed after 10 msec.

The shift of the trajectory of the accelerated electron away from the axial line of the plasma pinch is easily estimated from the known approximate formula[11]

$$\Delta\cong\frac{mvc}{eB_\varphi(a)}\frac{a}{R}=\frac{pc}{eB_\varphi(a)}\frac{a}{R}. \qquad (16)$$

In the relativistic case $\varepsilon\cong pc$, and consequently

$$\Delta\cong\frac{\varepsilon}{eB_\varphi(a)}\frac{a}{R}=\frac{\varepsilon}{B_\Theta}q(a),$$

where $a(a)$ is the stability margin and B_Θ is the longitudinal magnetic field. Assuming with a certain degree of arbitrariness $\varepsilon=12\times10^6$ eV and using for $q(a)$ and B_Θ their T-10 values, we obtain a value on the order of several centimeters for Δ. The experimental value of δ, i.e., the total displacement of the pinch in the course of the acceleration, agrees with these rough estimates.

An interesting feature of this discharge pulse is the two-step burst of voltage and of neutron emission. One can hardly doubt that in this case we are witnessing two successive formations of relativistic electron beams.

Following the recent TFR experiments[12] there is no

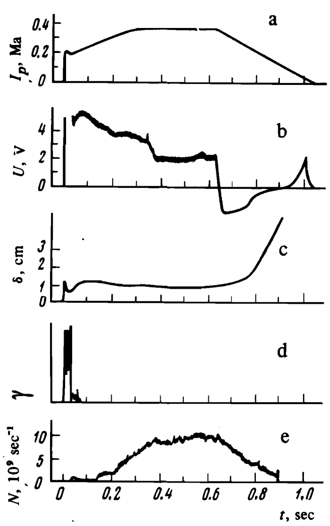

FIG. 3. Oscillograms of typical "normal" T-10 regime: a) current in plasma, b) torus curcuit voltage, c) horizontal displacement of plasma pinch, d) hard x rays, e) neutron emission.

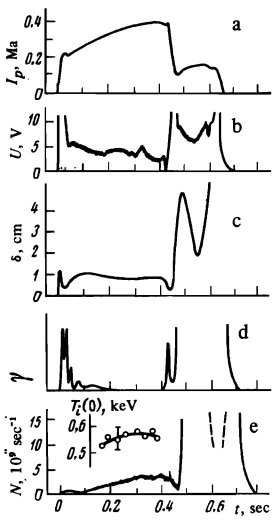

FIG. 5. Oscilligrams of acceleration regime (neutron yield 4×10^{12}): a) current in plasma, b) torus circuit voltage, c) horizontal displacement of plasma pinch, d) hard x rays, e) neutron emission and ion temperature as determined from charge exchange (circles) and from the neutrons (solid curve under the assumption $T_i=T_i(0)(1-x^2)^2$).

shadow of a doubt that the target for the photodisintegration process is the restricting diagram. We therefore merely mention the fact that the system of x-ray sensors placed around the installation indicates in our case clearly that the x-ray source is located in the region of the diaphragm.

Let us dwell on the question of the intensity of the neutron emission in acceleration discharges (it is immaterial of course in our case whether the discharge takes place in the hydrogen or in the deuterium). The number of discharges in the case of spontaneous development of the acceleration was small (10 out 300). Special experiments was therefore performed, in which the acceleration regime was purposely induced. To this end, the applied vertical controlling magnetic field was such as to ensure an initial inward pinch displacement of the required size towards the system axis. As a result, acceleration regimes were systematically observed (a total of 11 discharges) with high neutron yields. The average value of $R_{\gamma,n}$ in these experiments was about 6×10^{12} neutrons/pulse, larger by three or four orders of magnitude than the thermonuclear neutron yield in normal regimes. Unfortunately we are unable to measure directly the relativistic beam current, which is part of the total plasma current, so that a direct check of (7) is impossible. It is of interest, however, to estimate the value of I_e that should correspond to the observed neutron-emission intensity in the acceleration regime. The restricting diaphragm, which serves as a target for the electron beam in T-10, is made of an alloy of tungsten (85%) and molybdenum (15%). We thus know the variation of the quantity $\sigma_{\gamma,n}(\varepsilon)$.

The final energy acquired by the electron in acceleration discharges depends on the torus circuit voltage and on the duration of the acceleration. In principle, electrons can be accelerated to relativistic energies on the order of 10–15 MeV both in the "quiescent stage of the discharge, under the influence of a voltage 2–5 V for 0.2 sec., and during the short break (5–10 msec) under the influence of the large inductive circuit voltage. In the "quiescent" stage of the discharge, however, no distortion of the soft x-ray spectrum is observed (this distortion would attest to the presence of accelerated electrons). In addition the value of the neutron emission agrees fully with the measured ion temperature determined from charge exchange (see Fig. 5), so that there is no need to resort to deuterium electrodisintegration due to the presence of accelerated electrons. The macroscopic characteristics of the discharge in this stage do not differ from the characteristics of the "normal" discharges, so that the development of the beam of fast electrons in the "quiescent" stage of the discharge is not very likely. What seems more natural is acceleration of the electrons during the course of the break itself, under the influence of the inductive component of the voltage. Such a picture agrees well with the time dependence of the plasma displacement during the break (see Fig. 5), which was already discussed above.

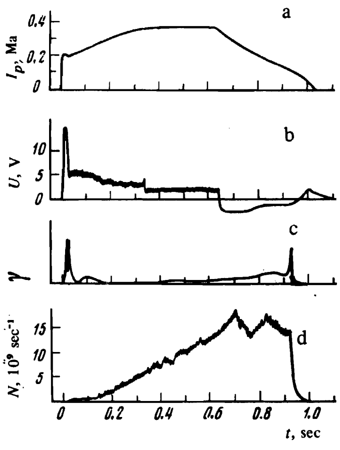

FIG. 6. Oscillograms of one of the T-10 discharges: a) current in plasma, b) torus circuit voltage, c) hard *d* rays, d) neutron emission.

Assume that the final beam energy is $\varepsilon=12$ MeV and consequently

$$\sigma_{\gamma,n}(\varepsilon)\cong200\ \text{mb}\,.$$

Then, after substituting the chosen values of $\sigma_{\gamma,n}$ and assuming $\bar{\rho}=17.3$ g/cm^3, $\bar{A}=171$, and $l=2$ cm, we can rewrite (7) in the form

$$R_{\gamma,n}\cong4\cdot10^8\ I_e. \qquad (17)$$

Thus, the neutron yield observed in T-10 in the acceleration mode corresponds to an electron current on the order of several dozen kiloamperes.

The effect connected with the electrodisintegration of the nuclei of a deuterium plasma is difficult to separate from the background of the thermonuclear emission without an energy analysis of the reaction products.[13] This was not done in the present series of experiments. It remains to discuss the modest possibilities afforded by an analysis of the time evolution of the neutron emission and a comparison of the estimated yield of the (e, n) reaction with the observed intensity.

Among the numerous neutron-yield oscillograms one encounters some frames in which the decrease of the plasma current during the final stage of the discharge, and consequently the drop in the ion temperature, is not accompanied by a corresponding decrease of the neutron yield, which remains at a fixed level or may even increase (Fig. 6). At the same time, the hard x rays increase in intensity. It should be noted that the neutron emission in the intermediate stage of the discharge (0.2–0.6 sec) agrees well enough with the measured ion temperature.

A likely qualitative interpretation of the observed effect is the following: At a certain instant of time, a group of "detached" electrons is produced in the plasma. The spatial displacement of the pinch, however, is such as to preclude the development of a relativistic beam with energy sufficient for the (γ, n) reaction. No giant pulse of neutron emission is therefore produced. At the same time, the energy of the relativistic beam (say 5–6 MeV) is sufficient for the (e, n) reaction to take place and be followed by a flash of bremsstrahlung when the beam is stopped. In other words, the neutron emission is "stretched out" on account of the (e, n) reaction.

Using (15), we can estimate the accelerated-electron current sufficient for the onset of the observed neutron emission. Assuming $\varepsilon \cong 5$ MeV and $n_d = 10^{13}$ cm^{-3} and using the values of $\sigma_{e,n}(\varepsilon)$ of[14], we obtain $I_e \cong 10$–15 kA. We note that if we attribute the unusual course of the neutron emission to the (γ, n) reaction on the diaphragm, this would call for an accelerated-electron current of only several amperes.

4. CONCLUSION

1. The stable neutron yield observed in "normal" regimes, amounting to 2×10^9 neutrons per discharge, agrees fully in magnitude and in time dependence with the preliminary estimates of the thermonuclear emission at the given current strength and deuterium density.

2. The giant yield 10^{12}–10^{13} neutrons per discharge, observed in the acceleration regimes, is due to (γ, n) reactions in the restricting diaphragm, and corresponds to a relativistic electron beam current of several dozen kiloampere. A rough model of free acceleration of a detached group of electron in the vortical electric field and of radial drift of the electron trajectory agrees with the time variation of the torus circuit voltage and with the spatial displacement of the plasma pinch.

3. It is plausible to relate the anomalous course of the neutron emission in the concluding stage of certain discharges with the development of an (e, n) reaction in the plasma under the influence of a weakly relativistic beam having an energy lower than the threshold of the (γ, n) reaction on the diaphragm.

In conclusion, the authors thank V. S. Mukhovatov, K. A. Razumova, V. S. Strelkov, and V. D. Shafranov for a useful discussion and S. E. Lysenko for the numerical calculations.

[1)] The significance of this agreement, of course, must not be overestimated, since the complicated calibration procedure yields the experimental values of $\bar{N}$ only accurate to a numerical factor ~ 2.

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Stability of high-frequency discharges under strong skin-effect conditions

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The stability of high-frequency discharges under strong skin-effect conditions is investigated with an inductive discharge in a gas stream as an example. An approximate method is developed for the study of the stability of different types of high-frequency discharges under various conditions. An analysis of a criterion is formulated for the stability of high-frequency discharges to one-dimensional perturbations and its analysis shows why discharges in molecular gases become unstable when the thermal-conductivity coefficient decreases as a function of the temperature.

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1. INTRODUCTION

By now there are many papers devoted to various aspects of the stability of a gas discharge and covering the range from a high-temperature plasma to a glow-discharge plasma. There is, however, a patent lack of studies of the stability of stationary high-frequency discharges, which are of great practical importance, notwithstanding the availability of various experimental data attesting to the important effect of the instability on the combustion conditions in discharges of this type. Thus, a discharge in hydrogen was observed[1] to change from