THE PLASMA PARAMETERS AND NEUTRON YIELD AT DEVICE OF "PLASMA FOCUS»

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In this work, calculations and experimental studies on the formation and dynamics of plasma in the "plasma focus" installations are carried out. Physical conditions were determined and critical parameters were calculated for estimating the neutron yield for kilojoule and megajoule installations. The results of plasma diagnostics and flow formation in the CPA-30 and PF-4 installations are shown. A comparison of calculated data and experimental values is performed. The value of the neutron yield parameter is justified and the possible cause of the appearance of saturation is indicated. The rationale for the development of further research in the direction of creating conditions for thermonuclear fusion in installations of the plasma focus type is given.

Keywords: neutron yield, plasma focus, activation detector, electrode

Introduction

The tasks of creating powerful sources of neutron fluxes and X-ray radiation are relevant for a number of industries of production and medicine, but the problem of solving the problem of thermonuclear fusion is even more acute. One of the new developing approaches in the creation of thermonuclear installations is the method based on plasma generation in installations of the plasma focus type. Plasma focus (PF) is a pulsed unsteady clot of high temperature dense hot plasma. When using deuterium as working gas, the PF is a localized source of neutrons and hard radiation. However, when using other materials, such as boron, the synthesis reaction may be without a neutron yield, but in this case, the energy yield of the reaction will be different. Therefore, the study of the possibilities of using plasma focus in thermonuclear energy is very important.

The phenomenon of "plasma focus" was discovered independently in the middle of the twentieth century by N.V. Filippov (USSR) [1] and J. Mather (J. Mather, USA) [2] in studies conducted under the program of controlled thermonuclear fusion. PF attracted interest by researchers, when the working chamber of the PF was filled with a rarefied isotope of hydrogen with deuterium, a powerful short impulse of fast neutrons and X-rays is generated inside the chamber of the discharge current. The discharge current usually measured in hundreds of kiloamperes [3,4. The first PF installations had an energy reserve of 50 kJ. In this case, the neutron yield achieved at these facilities was ~10^9 neutrons per pulse. The duration neutron pulse of the PF amount is t ~ 100 ns. From the practical point of view, installations with PF are used as sources of neutrons and hard radiation for solving a number of scientific and technical problems: materials science and blanket tests for controlled thermonuclear fusion; neutron therapy; pumping laser media; interactions of powerful beams with plasma, etc. In recent years, the direction of creating more compact devices has been developing [5, 6].

In the world have more than a dozen PF installations: the PF-1000 installation (Warsaw, Poland) has a capacity of 1 MJ, the Tulip plasma installations with power from 4 kJ to 0.4 MJ (Moscow, Russia), and others [7-8]. Previously, the authors conducted experiments on a pulsed plasma accelerator PF-30. The power of the CPA-30 installation is 35 kJ, the discharge current is 450 kA, and the duration is 7 µs. In this installation, formed dense and discharge plasma clots and their dynamics were studied, as well as the basic laws of plasma beam focusing, have been studied [9]. In particular, it has been shown that the dynamics of light and dense plasma flows differ significantly not only in flow rate but also in the role of ions in plasma acceleration and the whole structure of the plasma flow [10].

The use of focus plasma in thermonuclear reactors was considered in [11–12]. With an adequate level of understanding of these processes, new perspectives are emerging for the creation of a fusion reactor based on new data. Therefore, it is necessary both to study the possibility of creating an alternative type of thermonuclear reactor at the plasma focus installations and to conduct experiments on existing installations. In this paper, the problem is posed to theoretically calculate the parameters of the neutron yield and then compare it with the experiment.

1. Theoretical part.

A feature of the plasma focus-type installations is the dependence of the neutron yield on the energy E stored in a capacitor battery, and accordingly on the magnitude of the discharge current at the moment of pinching I_p:

$$Y_n = 10E^2 \quad (1)$$

$$Y_n = 10^{-13} I_p^4 \quad (2)$$

The PF installations of the kilojoule range, the inductance of the discharge chamber and the plasma column can be neglected, and then the discharge inductance will be determined by the inductance of the battery and lead wires. The value of the maximum discharge current for these installations is found by the formula (2), taking into account the energy stored in the capacitor battery is equal to:

$$I_m = \sqrt{\frac{2E}{L}} \quad (3)$$

Expressing the energy from equation (6), and substituting the resulting expression into equation (3), we obtain

$$Y_n = 2{,}5 \cdot I_m^4 L \quad (4)$$

From equation (6) it follows that the neutron yield for installations with kilojoule power is determined by the magnitude of the maximum discharge current.

The practical evaluation of formula (4), was calculated the neutron yield value for the PF-30 experimental setup. The capacitor battery consisted of 9 to 18 capacitors, each with a capacity of 3 μF and an inductance of 10^{-7} H. The maximum battery voltage is 30 kV. The maximum neutron yield for an installation with a capacitor battery with a capacity of 27 μF (9 capacitors) was $1.5 \cdot 10^9$ neutrons/pulse, and for a battery with a capacity of 54 μF (18 capacitors) consist $5.9 \cdot 10^9$ neutron/pulse.

The electron concentration can be found using the following expression for the electrodynamic model:

$$n_e = \frac{I^2 f_0 \mu_0 t}{4\pi\varepsilon r^2} \quad (5)$$

where I – current, f_0 – frequency, μ_0 - magnetic constant, r – the distance between the electrode, ε – ionization energy. From equation (5) it follows that the concentration of electrons depends on the current and the distance between the electrodes, which is illustrated in figure 1. It is seen that the electron concentration decreases with increasing anode radius. The change in the current of the circuit also affects the concentration of electrons, namely an increase in current leads to an increase in concentration. In addition, it can be seen that an increase in the electron temperature is affected by an increase in the current, but at the same time, the pulse time decreases. If the maximum current value is 1 MA, the electron temperature will take its maximum value of 126 eV, and the pulse time will be a minimum of 1 μs. More accurate determination of the maximum electron temperature, it is necessary to calculate the optimum ratio of the dimensions of the anode and cathode. The obtained data allows us to determine the values of the electron temperature when the anode radius varies from 0.25 cm to 2.25 cm.

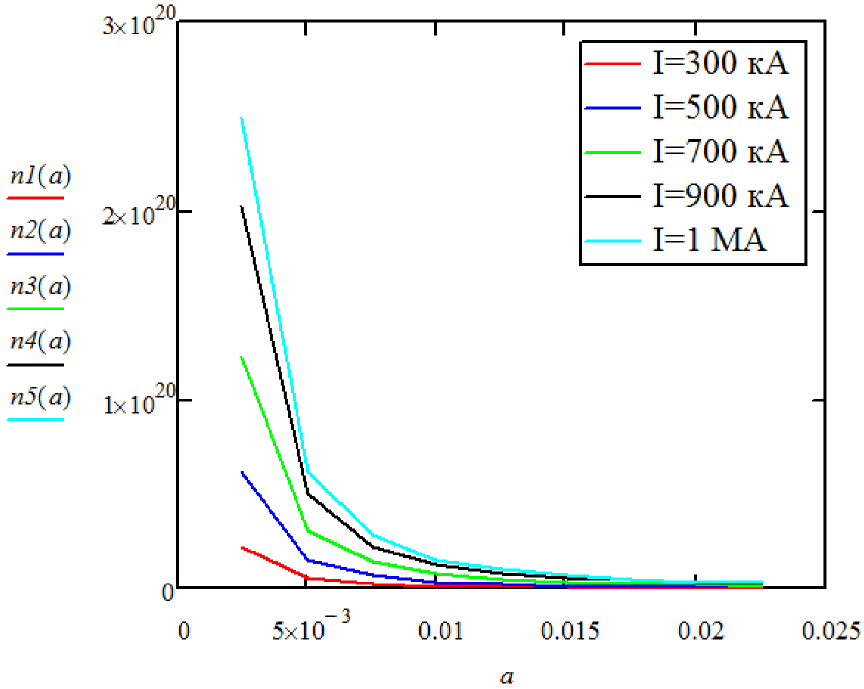


Fig 1 – Changes in the concentration of electrons from the distance between the electrodes for different values of current

Thus, the maximum temperature and electron concentrations were $2.5\cdot10^{16}$ cm^{-3} and 126 eV, and the neutron yield for the PF-30 installation may be $5.9\cdot10^{9}$ neutron/pulse. Calculations on the electrodynamic model show that the electron concentration decreases with increasing anode radius. At the same time, an increase in current leads to an increase in concentration. It was also found that an increase in the electron temperature is influenced by an increase in the current, but at the same time, the pulse time is reduced.

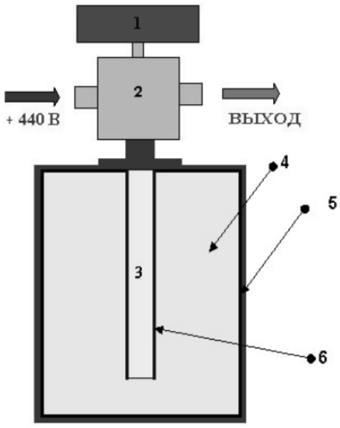
2 Measurement of neutron yield

To register a short duration neutron exit from pulsed sources of the Plasma Focus type at the P.N. Lebedev Physical Institute of Russian Academy of Sciences, a special detection system was developed, described in detail in [1]. The task was to develop equipment for the registration of neutron radiation of the DD reaction for PF type installations of relatively low intensity ($5\cdot10^{6}$–$2\cdot10^{7}$ neutrons per discharge) under conditions of powerful fluxes of electromagnetic plasma radiation in the presence of intense electrical and magnetic interference, the calibration of this system. Measurement of neutron fluxes in these conditions can be successfully carried out using activation detectors.

Activation detectors allow it possible to make measurements with a shift in time with respect to the moment of plasma generation after extinguishing of electromagnetic radiation and the cessation of interference. Measurements produce on standard equipment and with greater accuracy than the accuracy achieved indirect measurements of the amplitude of the neutron pulse.

The halogen Geiger counters CTC–5 (CTC–6) used as sensors in these detectors (Figure 2) were wrapped with indium (or silver) foil and placed in the center of the cylindrical moderator box. The type of sensor used has a relatively large "dead time" (~100 µs). Therefore, when measuring large neutron yield, it is also important not to have an excessively large number of samples on the recording equipment in order to minimize the errors of the recording system due to the relatively large resolution time of the system on the counting input.

The activation detector variant with the CTC–5 sensors are characterized by lower sensitivity as compared to activation detectors of similar types, as the detector has a relatively small container – moderator and the CTC–5 sensor itself has small dimensions compared, for example, the CTC–6 sensor with similar properties with, respectively, fewer counting on the measuring equipment. Measurements of neutron fluxes under these conditions can be successfully carried out using activation detectors [1,2,3,4].



1 – battery power supply of the electric circuit; 2 — electrical diagram of the activation counter; 3 — halogen Geiger counter CTC–5 (CTC–6); 4 — cylindrical block of activation counter retarder; 5 — the layer of cadmium; 6 — activated foil (In or Ag).

Fig 2 — Neutron detector developed in P.N. Lebedev Physical Institute of Russian Academy of Sciences

Let the detector be irradiated with fast (2.5 MeV) neutrons from a constant source of intensity I (neuter./sec.) located at the point from which the detector is visible at a solid angle Ω. Thermal neutrons (after the process of slowing down fast neutrons) inside the moderator block activate foils that wrap the sensor. In general, the absolute neutrons yield:

$$N + \Delta N - \overline{N}_{ph}^{\Delta t} = I\left(\frac{\Omega}{4\pi}\right)\left[\varepsilon' T'\left(1-e^{-t_1/T'}\right)e^{-t_2/T'}\left(1-e^{-\Delta t/T'}\right)+\varepsilon'' T''\left(1-e^{-t_1/T''}\right)e^{-t_2/T''}\left(1-e^{-\Delta t/T''}\right)\right].(6)$$

The indices “one stroke” and “two strokes” refer respectively to the parameters for indium isomers In^{116} and In^{116m} or the isotopes Ag^{108} and Ag^{110}. Description of other parameters in the formula (6) is given in [8,9].

The results of experiments on measuring the neutron yield at the PF-4 installation are shown in figures 3 and 4 for indium and silver foil respectively, used as a fast neutron moderator.

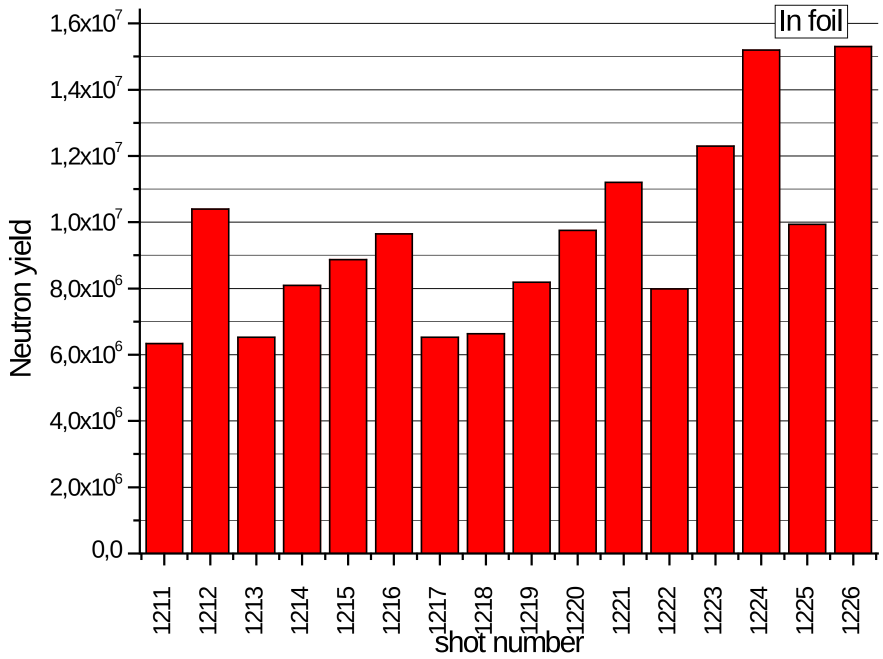


Fig 3. PF-4 neutron yield with indium foil

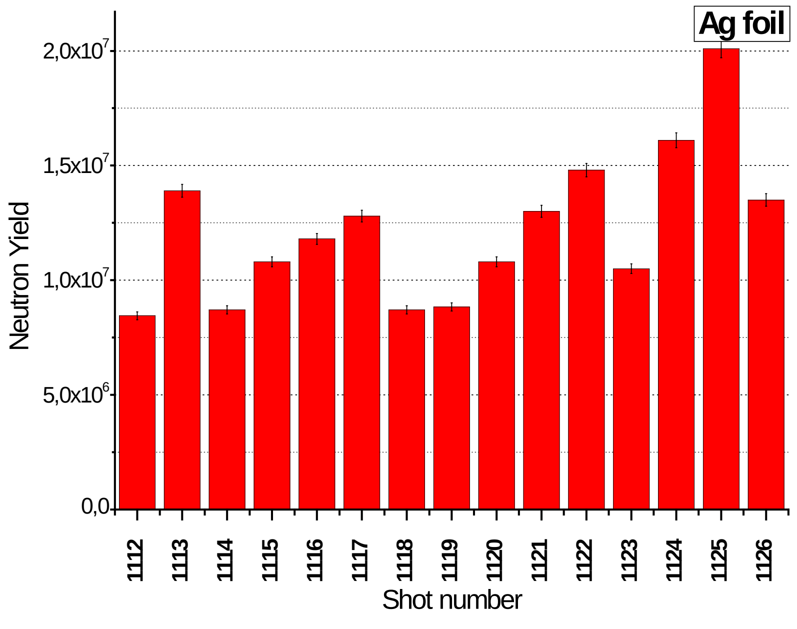


Fig 4. PF-4 neutron yield with silver foil

3. Conclusion

The results of calculations and experiments shown that for installations like plasma focus PF-30 and PF-4 it is possible to obtain discharge currents of hundreds of kiloamperes and current rise rates up to ~ 10^{11} A/s. The current data determined from the experiments and the plasma parameters agree with the calculated values given above. At the same time, the neutron yield was calculated on the basis of the thermodynamic model, i.e. a priori assuming its thermonuclear origin. But a review of the experimental facts suggests that neutron emission may be associated with other conditions and is not characteristic only of "plasma focus". For example, the neutron flux was also observed on high-voltage gas discharges with a specific geometry of the electrodes, creating field strength sufficient for "runaway of electrons" [13]. In this case, the typical times of processes are counted in hundreds of nanoseconds, which are also observed for a plasma focus.

Previously reported experimental work that when using deuterium gas in the PF, neutron yield is observed with the energy distribution along the axis of the system and energy of 2.45 MeV. Neutron radiation had an isotropic distribution and its duration was of the order of tens of nanoseconds. It was assumed that these neutrons are of thermonuclear origin, which leads to isotropic neutron radiation. However, the result of measuring the anisotropy of the neutron yield along the axial z and radial φ directions was equal to $Y_n(z)/Y_n(\varphi) \sim 2 \div 3$, which contradicts the thermonuclear mechanism. In addition, the average energy of neutrons in the axial direction was greater than the energy of thermonuclear neutrons (2.45 MeV). This fact indicates that it is worth considering the non-thermal mechanism of neutron emission.

Thus, today, both thermonuclear and beam emission options are possible, but the details and mechanism of ion acceleration still need to be clarified.

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