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ON POSSIBILITY OF REFLECTIVE TRIODE USES FOR THERMONUCLEAR NEUTRON GENERATION IN BUDKER-POST TRAP WITH PULSED MAGNETIC FIELD

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Abstract

The scheme proposed is meant for the generation of thermonuclear neutrons in a pulsed plasma trap with magnetic-inertial confinement of plasma. A high-temperature plasma region, which mainly produces neutrons, is formed in the center due to the interaction of two counter-axial streams of deuterons and heavy jets of hydrogen, injected perpendicular to the axis of the trap. The evaluation showed that the fusion mechanism of generation of neutrons dominates the direct interaction of the "beam-plasma".

INTRODUCTION

A scheme for generating thermonuclear neutrons in a pulse trap with magnetic and inertial plasma containment is proposed. A high-temperature region of plasma wherein neutrons are mostly generated is formed in the center due to the interaction of two countercurrent axial deuteron streams and a stream of heavy hydrogen injected perpendicular to the trap axis.

Figure 1 demonstrates a variant of the said scheme for neutron generation with a heavy hydrogen isotope injector.

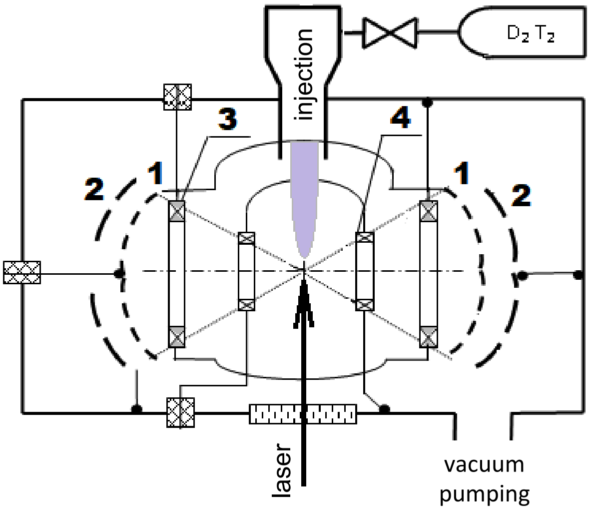

Figure 1: Scheme of the thermonuclear neutron generator (1 – diode accelerator anode; 2 – its cathode; 3 – focusing coils; 4 – magnetic trap).

The injection of heavy hydrogen can be carried out using several methods. One of the variants of realization of a pulse heavy hydrogen isotope injector may be a laser ion source with a plasma-forming target saturated with heavy hydrogen, with a conical cavity, the axis of which is directed to the center of the magnetic trap. In order to provide laser radiation feed to the gun, a hermetic optical window is designed in the casing of the device.

Another variant for realization of a pulse heavy hydrogen isotope injector may be a pulse plasma accelerator, e.g. of the "rail gun" type.

In order to accelerate the plasma heating process at energy transfer from the accelerated protons to electrons, the device may further contain a generator of a gas stream with a high number in the Periodic Table (e.g. xenon or iodine vapors). Thereby, the electron concentration in the trap may be increased by about 2 orders of magnitude.

The principle of generator operation

The control unit transmits a signal to start the pulse deuterium and/or tritium isotope injector, and the stream of these isotopes is formed directed to the magnetic trap. The time of continuous generation of the heavy hydrogen isotopes stream is about several milliseconds. Simultaneously with the injection start, the start of the pulse current generator and the formation of the magnetic field in the generator working volume are carried out. Several decades of nanoseconds prior to the achievement of the maximum value of the magnetic field induction, the start of the high voltage pulse generator is carried out; it may be designed, e.g. basing on the Blumlein line or the Arkadiev-Marx scheme. The amplitude and duration of the high voltage pulse $U(t)$ should thus be in the ranges of (0.5-1) MV and (50-100) ns correspondingly. The authors have developed such a pulse voltage source, allowing a repetitively pulsed mode of operation with a frequency of up to 10 Hz [1].

At the cathode surface, as well as at the metallic inserts on the shells of the focusing coils, a strong electric field is formed providing for conditions for effective emission of electrons accelerated to the anode and oscillating in the region adjacent to it, forming a virtual cathode. Under the effect of electron bombardment of the anode electrode, the following processes occur: heating of the anode, desorption of heavy hydrogen from the saturation region, formation of anode plasma, extraction of hydrogen nuclides from the plasma and acceleration of nuclides to the direction of the virtual cathode formed in the focusing coil region, to the direction of the magnetic trap. Both diode systems thus function in the reflective triode mode [2].

CALCULATION-THEORETICAL MODEL

From the solution of the self-matching Poisson equation, the following formula is obtained for a possible approximated dependence of the total current of protons dissipated

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in the plasma inside the magnetic trap and providing for its heating:

$$I(t) \approx 1.86 I_A \sqrt{\frac{m}{M}} \left(\frac{R_k}{R_A - R_k}\right)^2 [1 - p(1+p^2)^{-1/2}] \left(\int_1^{1+\frac{eU(t)}{mc^2}} du (u^2-1)^{-1/4}\right)^2,$$

wherein R_A and R_K are the radii of the anode and cathode spherical sectors, correspondingly, I_A is the Alfven current, m, M are electron and proton weights, correspondingly, e is the elementary electric charge, c is light speed, $p = d/2a$, d is the distance between the magnetic trap coils, a is the coil radius.

According to the outlined schemes, the coils of the magnetic trap and the coils of the proton focusing system creating the total magnetic field are fed with current pulses $I_{1,2}(t)$, correspondingly, which may be approximated by sinewaves with the amplitudes

$$I_{01,2} \approx U_1 \sqrt{\frac{C}{2L_{1,2}}},$$

wherein C is the value of the accumulated capacity in the pulse current source circuit, $L_{1,2}$ are coil inductivities.

In order to provide for the magnetic localization of the accelerated protons in the trap volume in the lateral direction, it is necessary for the maximum Larmor deuteron radius in the trap to be not higher than the coil diameter:

$$\frac{1}{B_0} \sqrt{\frac{2MU_0}{e}} \le a,$$

wherein e is the elementary electric charge, and the formula

$$B_0 = \frac{\mu_0 w_1 I_{01}}{a(1+p^2)^{3/2}}$$

is the amplitude of the magnetic field induction in the center of the trap (μ_0 is the magnetic constant, w_1 is the number of threads in the coil).

Figure 2 demonstrates the calculated family of the magnetic field amplitude distribution over the device symmetry axis – $B(p,z)$.

The computer analysis has shown that the maxima closest to the center are achieved at the locations of the magnetic trap coils:

$$B_{1\text{M}} \approx B(p, 0.5d) \approx \frac{\mu_0 w_1 I_1}{2a} \frac{1 + (4p^2+1)^{3/2}}{(4p^2+1)^{3/2}},$$

and the distant maxima correspond to the locations of the focusing coils:

$$B_{2\text{M}} \approx B(p, D) \approx \frac{\mu_0 w_2 I_2}{R_\Phi}.$$

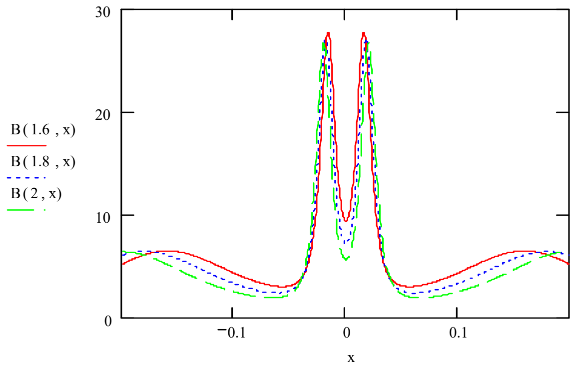

Figure 2: Calculated family of the magnetic field amplitude distribution over the device symmetry axis.

In order for all the protons accelerated in the diodes to enter the trap, the following condition should be met:

$$\frac{R_\Phi}{R_A} \approx \sqrt{\frac{B_{2\text{M}}}{B_{1\text{M}}}},$$

which follows from the adiabatic invariability of the relation of the kinetic energy of the lateral proton movement to the magnetic field induction [3].

The calculation has shown that for effective generator operation, the following conditions should be imposed upon its parameters:

$$\frac{Uw_1}{(1+p^2)^{3/2}} \sqrt{\frac{C}{U_0 L_1}} \ge \frac{2}{\mu_0} \left(\frac{M}{e}\right)^{1/2},$$

$$\frac{aw_2}{R_K w_1} \left(\frac{L_1}{L_2}\right)^{1/2} \cong \frac{1 + (1+4p^2)^{3/2}}{(1+p^2)(1+4p^2)^{3/2}},$$

When the accelerated protons enter the inner region of the magnetic trap, they are dissipated and decelerated in the hydrogen isotope stream from the injector, forming high-temperature plasma due to heating of the electron component with subsequent thermolization. The deceleration process is described by the following differential equation:

$$\frac{dV}{dt} = -\frac{1}{M} F\left(\frac{MV^2}{2}\right),$$

wherein $F(T)$ is the dependence of the energetic proton losses in plasma per the length unit to kinetic energy, $V(t)$ is the velocity of the accelerated protons in the trap. The computer analysis has shown that the time of pumping of energy of the accelerated proton stream to plasma formed in the magnetic trap is ~10^{-2} ms. In such a long period of time, the process of deuteron stream formation itself in the diode system may be regarded as almost instant.

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Basing on the considerations outlined above, a differential equation may be compiled that describes a process of plasma hearing in the trap:

$$n\frac{d\theta}{dt}=\frac{1}{\pi e}F[\frac{MV(t)^2}{2}]\frac{V(t)}{a^2d}\int_{t_1}^{\tau+t_1}duI(u)-\sqrt{\frac{2e}{5\pi M}}\frac{pn}{a}\Delta\Omega(p)\theta^{3/2},$$

wherein θ is plasma energetic temperature (keV), n is the total concentration of hydrogen isotopes in the plasma, t_1 is the time of delay between the high voltage pulse and the start of the hydrogen isotope stream generator,

$$\Delta\Omega\cong 2\pi[1-p(1+p^2)^{-1/2}].$$

The negative member in the right part of the differential equation takes into account the correction for a possible deuteron escape from the magnetic trap in the longitude direction.

The described process of plasma heating was examined during a computer experiment. The obtained temperature to time plots allowed calculating a stream of the generated thermonuclear neutrons. The most interesting case was examined, when the hydrogen isotope stream created by the injector consisted of deuterium and tritium components and for the formation of neutrons a nuclear reaction T(d,n)^{4}He was used. The stream of the thermonuclear neutrons from the plasma into the full solid angle was assessed according to the formula:

$$Q(t)=10^{-28}\pi a^2d\frac{n^2}{4}\sigma[\frac{5.10^{-3}}{2}\theta(t)]\sqrt{\frac{4e}{3\pi M}\theta(t)},\ \cdot$$

wherein

$$\sigma(T_d)=\frac{5.8\cdot 10^4}{T_d}\frac{\exp(\frac{17.2}{\sqrt{10T_d}}}{1+\frac{(T_d-96)^2}{174^2}}$$

is the dependence of the micro cross section of the T(d,n)^{4}He nuclear reaction to the deuteron kinetic energy in the laboratory coordinate system [4].

CONCLUSION

The calculation has shown that at linear sizes of the device of ~0.1 m, the accelerating pulse amplitude of 5□10^5 kV and the duration of ~100 ns it is possible to obtain up to 10^{12} neutrons per pulse. The use of the small-sized pulse voltage generator device developed by the authors capable of realizing the said electrophysical pa parameters with a frequency of up to 10 Hz makes the project of the proposed neutron generator quite competitive with the known classic neutron generators.

In order to confirm this statement, a variant of the generator has been studied, wherein not protons but deuterons should be accelerated in the diode system. In such a device, apart from the thermonuclear neutron generation channel, a channel of neutron generation exists at direct interaction of the accelerated deuterons with hydrogen nuclides from the plasma injector. The calculation has shown that the stream of thermonuclear neutrons at the generator parameters examined above exceeds the stream of neutrons generated according to the beam-plasma channel, as well as in the classic neutron generator with a plasma or gas target.

The proposed device allows for significantly increasing the continuous working resource compared to classic proton generators with solid-state neutron-forming targets when using it as a neutron generator for solving the problems in elemental analysis, remote nuclear control, etc. Moreover, the proposed device may be a basis for the design of a small-sized controlled thermonuclear reactor operating in the repetitively-pulsed mode.

REFERENCES

[1] Vovchenko, E.D., Isaev, A.A., Kozlovsky, K.I., & Shikanov, A.E. (2017). An Accelerating Voltage Generator for Compact Pulsed Neutron Sources. *Instruments and Experimental Techniques*, 62(6), 968-970.

[2] Lukyanov, S.Yu., & Kovalsky, N.G. (1999). *Hot Plasma and Controlled Nuclear Synthesis*. Moscow: MIFI. (p. 431).

[3] Bystritzky, V.M., & Didenko, A.N. (1984). *Powerful Ion Beams*. Moscow: Energoatomizdat. (p. 152).

[4] Vlasov, N.A. (1971). *Neutrons*. Moscow: Nauka. (p. 552).