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PLASMA DIAGNOSTICS

Possibility of Achieving Thermonuclear Ignition by Magnetohydrodynamic Compression of a Solid Target by the Current of a Disc Explosive Magnetic Generator

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Abstract—One of the fields of thermonuclear research is gas-dynamic thermonuclear fusion based on spherical cumulative compression of deuterium–tritium (DT) gas using an explosive charge. Unfortunately, due to high compression asymmetry, it was not possible to achieve the ignition threshold, despite more than half a century of the development. The work considers an alternative path based on cylindrical cumulative compression of DT gas by a magnetic field. This method may be free from the drawback associated with compression symmetry. The possibility of achieving the ignition threshold in this way is shown by calculations. At the same time, modern technologies based on explosive magnetic generators make it possible to implement the conditions required for this. However, the analysis shows that the efficiency of converting magnetic field energy into thermonuclear neutron energy, DT plasma burnup, and neutron radiation yield are significantly inferior to the developed approach associated with the compression of preheated magnetized DT plasma (previously MAGO/MTF, now MagLIF).

Keywords: inertial thermonuclear fusion, disk explosive magnetic generators, preheating by a shock wave, plasma compression by a liner

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1. INTRODUCTION

In 1946, A.S. Kozyrev put forward the idea of the possibility of achieving pressures and temperatures high enough for thermonuclear reactions to occur in heavy hydrogen isotopes at the focus of a spherical charge of conventional explosive [1]. He also proposed the design of the first explosive device. This original direction of inertial thermonuclear fusion, based on spherical cumulative compression of deuterium–tritium gas (DT gas) using an explosive charge, was called gas-dynamic thermonuclear fusion (GDTF).

Theoretical calculations on GDTF were started at the All-Union (now All-Russian) Research Institute of Experimental Physics (VNIIEF) in 1951 by Ya.B. Zeldovich, N.A. Popov, and V.A. Aleksandrov. E.I. Zababakhin paid permanent attention to these works. Numerical estimates showed that in a charge of explosive with a radius of ~50 cm, it is necessary to ensure spherically symmetric convergence of the shell up to a radius of several tenths of a millimeter in order to create temperatures of ~2 keV, which is necessary for achieving ignition. Under these conditions, a thermonuclear flash could be excited in a DT mixture with a mass of $\sim 10^{-3}$ g [2].

Initially, experimental research on GDTF was carried out at the All-Russian Research Institute of Experimental Physics under the supervision of L.M. Timonin; in 1958, A.S. Kozyrev and his colleagues joined these studies. Over four decades, the employees of the All-Russian Research Institute of Experimental Physics N.A. Popov, E.I. Zababakhin, V.A. Shcherbakov, V.M. Danov and others proposed a number of improvements to the systems of spherical cumulative compression of deuterium–tritium gas. The maximum, record-high neutron yield of 5×10^{13} neutrons was recorded from a target containing DT gas with an initial radius of ≈1 mm and an initial density of ≈ 0.1 g cm^{-3} on December 10, 1982. According to estimates, the experiment achieved a temperature of ≈0.65 keV and a maximum density of ≈ 80 g cm^{-3}. A temperature 3–4 times greater is required for ignition of the DT gas. The experimental neutron yield was lower than the calculated one by 2–3 orders of magnitude in this experiment, as in all the others [3].

A detailed analysis of the works on GDTF is presented in a review [4]. In particular, it is noted that high requirements are imposed on the symmetry of compression and the permissible width of the mixing zone for the implementation of ignition of a low-mass thermonuclear mixture in GDTF systems. In this case, the main sources of asymmetry are located outside, for example, the initiation system of explosives.

In [5], it is proposed to compress a thermonuclear target with a deuterium–tritium mixture by a magnetic field. This method, on the one hand, is free from a significant source of symmetry, the initiation system of explosives, on the other hand, due to the absence of the mass of the magnetic field, energy cumulation can be implemented at large radii, which allows working with large-sized targets. The energy basis for the implementation of magnetogasdynamic energy cumulation can be the created explosive magnetic generators (EMG) [6].

Further, the development of magnetogasdynamic energy cumulation followed the path of compression of preheated magnetized plasma. Preheating reduces the requirements for the compression value, and magnetization reduces thermal conductivity losses and provides additional heating by α particles even at low plasma density. This concept of magnetic compression (MAGO)/magnetized target fusion (MTF) was developed both in Russia [7] and in the United States [8]. Preheating of the plasma is performed by a current pulse, and subsequent compression is performed by a liner system accelerated by the current of a more powerful source [9–14]. Unfortunately, due to the appearance of impurities of heavy elements in the preheated plasma, it was not possible to achieve its lifetime of ≥10 μs required for the implementation of the compression stage.

In recent years, the MagLIF project [15, 16] with preliminary heating of plasma by laser radiation (LR) has been developed in the United States at the Z facility. During compression, a yield of 2×10^{12} neutrons in the DD reaction was achieved [17]. The close values of the detected neutron yields with the calculated predictions indicate that, unlike the MAGO/MTF systems, impurities of heavy elements have no noticeable effect on the temperature of the compressed plasma.

The Z facility implements a current of up to 25 MA. The power should be an order of magnitude higher (current ≥65 MA [16, 18]) to achieve thermonuclear ignition. The creation of such setups based on capacitor banks is a matter for the future.

Calculations show [19, 20] that thermonuclear ignition can be achieved by compressing a DT plasma column ~10 cm long with cross section of ~1 cm^2, density of 2.5×10^{-4} g/cm^3, and initial temperature of ~250 eV by a current source with voltage of 2–3 MV and energy of 100–150 MJ. To create plasma with such parameters, laser radiation with wavelength of ~1 μm, energy of ~100 kJ, and pulse duration of ~25 μs is required. The current source can be implemented on the basis of modern disk explosive magnetic generators (DEMG) [21].

Thus, starting with GDTF systems in the 1980s, the development of magnetogasdynamic energy cumulation followed the path of compression of preheated magnetized plasma. In this work, an attempt is made to consider the prospects of an alternative path for the development of magnetogasdynamic energy cumulation: compression of a solid DT target by a cylindrical liner system to achieve thermonuclear ignition. In this case, the initial heating of the DT gas is created by a shock wave generated as a result of the liner impact on the target.

The basis for setting such a task at the present time may be

—implementation of a velocity of 50 km/s at a radius of 1 cm by a cylindrical liner system accelerated by a DEMG current (the achieved energy density is 200 times higher than the energy density of explosives) [22];

—achievement of the stable convergence of cylindrical liners down to radii of tenths of a millimeter (velocities of ~20 km/s) in precision experiments on studying the dynamic isentropic compressibility of substances at the Z facility [23];

—creation of the technology for the formation of EMG current pulses of at megavolt potentials [24, 25].

2. PROBLEM STATEMENT

The experimental scheme shown in Fig. 1 is considered. A shock wave is formed when the liner *2* accelerated by the current pulse *I* hits a target made of DT ice. If the density of the liner substance is much higher than the density of DT ice, then at a target impact velocity of ≥100 km/s, the temperature of the DT gas in the shock wave is $T \geq 40$ eV. Further adiabatic compression by $\delta_r \geq 10$ times along the radius leads to heating to thermonuclear temperatures $T \sim d_r^{2(\gamma-1)} \geq 1$ keV.

For thermonuclear ignition of DT plasma of mass M, the following condition should be met [26]

$$W = \frac{1}{M}\int_V\int_t \frac{Q_{nf}}{\varepsilon_T}\, dVdt \geq 0.3, \qquad (1)$$

where double W is the analog of the Lawson criterion for pulse systems, Q_{nf} is the power of thermonuclear energy release absorbed by a unit volume of plasma, ε_T is the specific energy of compressible plasma calculated disregarding the thermonuclear energy release (by cold gas).

We assume that neutrons leave the plasma, i.e., they do not contribute to Q_{nf}. The probability for an α particle to slow down in a DT plasma depends on the ratio R/λ, where R is the target radius, and λ is the

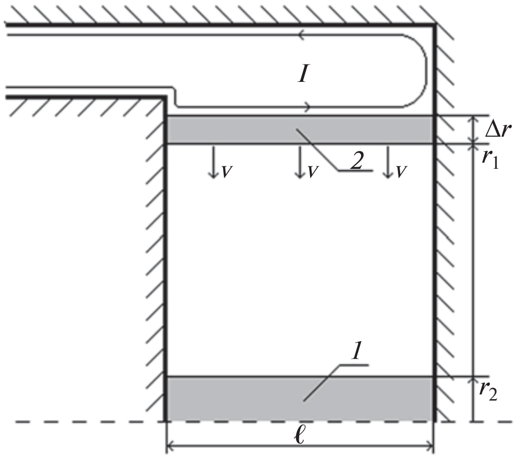

Fig. 1. Scheme of experiments: (*1*) DT ice; (*2*) liner.

range of an α particle. The simplest interpolation of this probability is sufficient for our purposes: at $R/\lambda \geq 1$ all the energy of α particles is absorbed by the plasma. Electrons of DT plasma slow down the α-particle to temperatures of $T \sim 30$ keV, and its range at densities of ~100 g/cm^3 is [27]

$$\rho\lambda = 3\times10^{-2}T^{5/4}\ \text{g/cm}^2. \quad (2)$$

We describe the dynamics of the liner and DT plasma by a system of one-dimensional equations of magnetohydrodynamics, which in Lagrangian coordinates ($s = \int_0^r \rho r dr$) has the form

$$\begin{cases} \dfrac{\partial}{\partial t}\left(\dfrac{1}{\rho}\right) = \dfrac{\partial}{\partial s}(rv), \quad \dfrac{dr}{dt} = v, \\ \dfrac{\partial v}{\partial t} = -r\dfrac{\partial(p+\eta)}{\partial s} - \dfrac{1}{r}\dfrac{\partial}{\partial s}\dfrac{(rH_\varphi)^2}{8\pi}, \\ \dfrac{\partial}{\partial t}\left(\dfrac{H_\varphi}{r\rho}\right) = \dfrac{\partial E_z}{\partial s}, \quad \dfrac{\rho}{4\pi}\dfrac{\partial(rH_\varphi)}{\partial s} = \sigma E_z, \\ \dfrac{\partial \varepsilon_T}{\partial t} + p_T\dfrac{\partial(rv)}{\partial s} = -\dfrac{\partial}{\partial s}(rS) - \eta\dfrac{\partial(rv)}{\partial s} + \dfrac{\sigma E_z^2}{\rho} + \dfrac{Q_{nf}}{\rho}, \\ S = -\chi_\perp r\rho\dfrac{\partial T}{\partial s}, \end{cases} \quad (3)$$

where quantities are measured in the following units: time [t] in μs; radius [r] in cm; velocity [v] in cm/μs; Lagrangian coordinate [s] in g/cm; density [ρ] in g/cm^3; total pressure and thermal parts of pressure [p, p_T] в 10^{12} erg/cm^3; specific energy [ε_T] in 10^{12} erg/g; numerical viscosity [η] in 10^{12} erg/cm^3; azimuthal component of the magnetic field [H_φ] in 10^6 G; longitudinal component of the electric field [E_z] in 10 kV/cm; conductivity [σ] in 10^3 (Ω cm)$^{-1}$; flows of thermal and radiant energy [S] in 10^{12} erg/(cm^2 μs); temperature [T] in keV; thermal conductivity coefficient [$\chi_\perp$] in 10^{12} erg/(cm^2 μs keV).

Equations (3) are solved in the region of the copper liner ($s_{Cu} \leq s \leq s_0$) and DT gas ($0 \leq s \leq s_{DT}$, $s_{DT} = s_{Cu}$) with initial conditions

$$\rho\big|_{t=0} = \begin{cases} \rho_{CU}, & r_1 + \Delta r \geq r \geq r_1, \\ \rho_{DT}, & r_2 > r > 0, \end{cases} \qquad r\big|_{t=0} = r_i^0,$$
$$v\big|_{t=0} = 0, \quad \varepsilon_T\big|_{t=0} = 0, \quad H_\varphi\big|_{t=0} = 0.$$

Initial densities of copper $\rho_{Cu} = 8.96$ g/cm^3 and DT ice $\rho_{DT} = 0.25$ g/cm^3, and r_i^0 are initial radii of the nodes of the difference grid.

Equations (3) are solved with boundary conditions of the form

—dynamic group: $v\big|_{s=0} = 0$, $(p+\eta)\big|_{s=s_0} = 0$;

—magnetic group: $H_\varphi\big|_{s=0} = 0$, $H_\varphi\big|_{s=s_0} = \dfrac{I(t)}{5r\big|_{s=s_0}}$;

—thermal group: $S\big|_{s=0} = 0$, $S\big|_{s=s_0} = 0$.

When a disk EMG with an electric explosion tripping device operates, the current in the load circuit is created by the voltage that occurs during the electric explosion of the foil. For simplicity, we assume that it is constant over time and equal to U_0. In this case, the current in the liner load $I(t)$ is determined from the solution of the equation of the following type:

$$\frac{d}{dt}\left[(L_0 + L(t))I(t)\right] + E\ell = U_0, \quad (4)$$

where L_0 is the initial inductance of the energy supply circuit,

$$L(t) = \frac{\mu_0\ell}{2\pi}\ln\left[\frac{r_1+\Delta r}{r}\bigg|_{s=s_0}\right],$$

the initial current $I|_{t=0} = 0$, $E = E_z$ ($s = s_0$).

The DT plasma can be considered as an ideal gas up to densities of ~100 g/cm^3 at temperatures ≥40 eV behind the front of the first shock wave [28]. Its conductivity σ, as well as the electron ℓ_e and ion ℓ_i, ranges determining the thermal conductivity coefficient $\chi_\perp = 4\sigma_{SB}T^3(\ell_i + \ell_e + 4\ell_R)/3$, were determined from [29], Rosseland mean range for radiation ℓ_R from [28]. Here, $\sigma_{SB} = 1.03 \times 10^{18}$ erg/(cm^2 μs keV^4) is the Stefan–Boltzmann constant.

The equations of state and conductivity of copper were determined from [30], and in accordance with [31], the conductivity is corrected $\sigma = \sigma(\rho, \varepsilon_T)(\rho/\rho_{Cu})^{2.27}$ at a density $\rho > \rho_{Cu}$, and it was considered that $\sigma(\rho, \varepsilon_T) = \sigma(\rho, \varepsilon_0)$ at $\varepsilon_T > \varepsilon_0 = 30$ kJ/g. The thermal conductivity of copper and the Rosseland mean range for calculating the radiant thermal conductivity were determined from [12, 32, 33]. The ionization degree was calculated in the average ion approximation [28].

It should be noted that significant progress has been made in the study of equations of state and transport properties of substances in recent years [34]. However, for a number of reasons, we use data from classical works. When describing the dynamics of a copper liner, it is important to have a system of consistent equations of state and conductivity. From this point of view, the system of [30] has proven itself very well in practice, although the equations of state of copper used in it are by no means "ideal." To maintain continuity with previously performed studies [4], we use data from [29] to describe the properties of the DT plasma.

The energy power of α particles released per unit volume of plasma is determined from

$$Q_{nf} = \frac{1}{4} E_\alpha (\sigma v)_{\mathrm{DT}} \frac{(\rho/m_p)^2}{A^2}, \qquad (5)$$

where m_p is the proton mass, $A = 2.5$ is the average atomic mass, $E_\alpha = 3.5$ MeV is the energy of the α particle, and $(\sigma v)_{\mathrm{DT}}$ is the thermonuclear reaction cross section [35].

The neutron radiation yield per unit time from a unit length of the plasma column is determined by the equation

$$\frac{dN_{\mathrm{TD}}}{dt} = \frac{1}{A^2 m_p^2} \frac{\pi}{2} \int_0^{s_{\mathrm{DT}}} (\sigma v)_{\mathrm{DT}} \rho \, ds. \qquad (6)$$

In the calculations, we assume the height of the liner ℓ to be equal to its initial radius $\ell = r_1$. As a rule, the liner remains stable when accelerated by a current pulse on a basis of no more than 10 of its initial thicknesses. Therefore, we assume the thickness of the liner to be equal to $\Delta r = 0.1 r_1$. A typical initial inductance of the energy supply to the load is $L_0 = 10$ nH. For a given potential U_0, the initial radius of the liner r_1 and the size of the target r_2 are varied in order to obtain the maximum double W (Eq. (1)). In this case, the r_2 value should be such that at the time of maximum compression, the radius of the target R exceeds the range of the α particle λ [2].

3. CALCULATION RESULTS

Figures 2–5 show results of solving Eqs. (3) by disregarding the thermonuclear energy release ($E_\alpha \equiv 0$ (5)) at a potential $U_0 = 5$ MV, initial liner radius $r_1 = 1.25$ cm, and the target size $r_2 = 0.025$ cm.

By the time the target surface $r = r_2$ is reached, the velocity of the inner surface of the liner reaches ~170 km/s, density ~75 g/cm³, and the magnetic field does not penetrate to the inner surface of the liner.

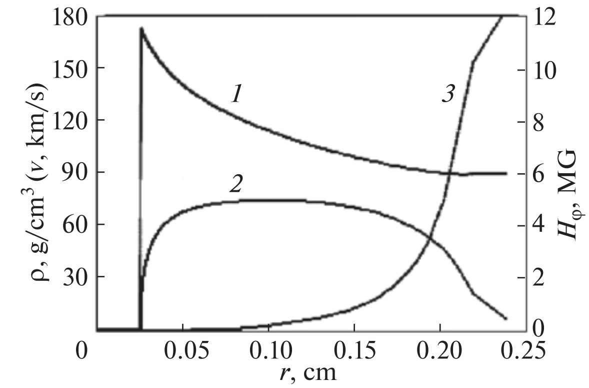

Fig. 2. Distributions of (1) velocity v, (2) copper density ρ and (3) magnetic field H_φ over the liner thickness at time $t = 0.505$ μs impact on the surface of the target made of DT ice.

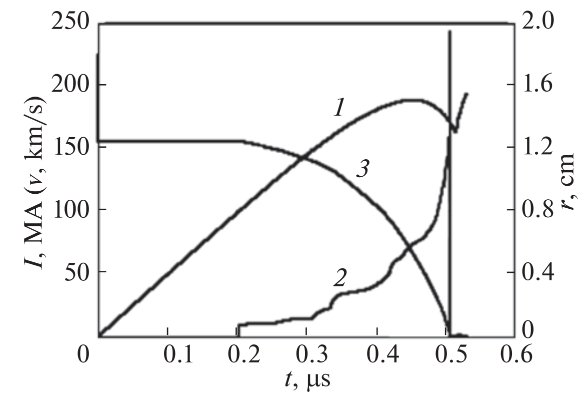

Fig. 3. Time dependences of (1) the current in the liner I, (2) velocity and (3) coordinate r of the inner surface of the liner.

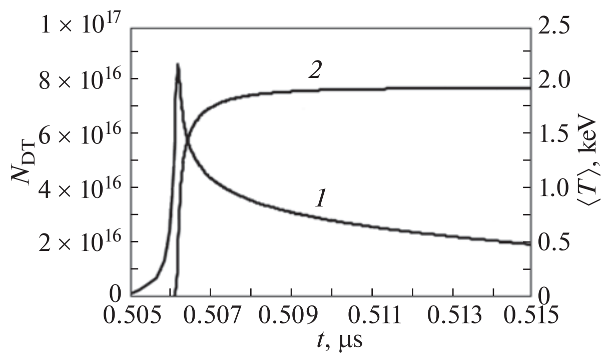

Fig. 4. Time dependences of (1) the average temperature of the DT plasma $\langle T \rangle$ and (2) the neutron radiation yield N_{DT}.

This is evident from the distributions of these quantities by the liner thickness shown in Fig. 2.

Figure 3 shows the time dependence of the current in a liner, the dynamics of the velocity and coordinates of the inner surface of the liner. The current reaches

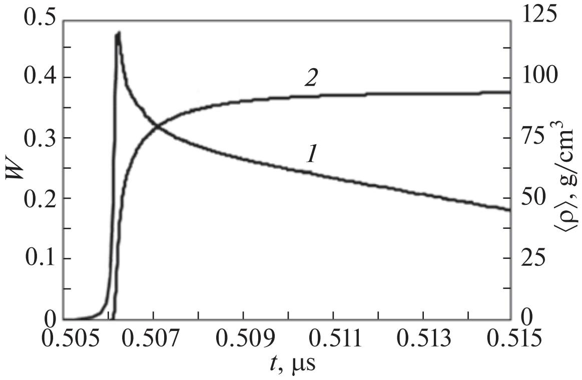

Fig. 5. Time dependences of (*1*) the average density of the DT plasma $\langle\rho\rangle$ and (*2*) the double W value.

~188 MA, and the time of the impact of the liner on the target τ_{imp} ~ 0.5 μs. The velocity of the liner surface increases to ~240 km/s in a time of ~1 ns after the interaction with the target. The energy of the current source required to create a liner with the given parameters is determined from $E_{el} = U_0\int_0^{\tau_{imp}} Idt \approx 300$ MJ.

Figures 4 and 5 show time dependences of the average temperature of the DT gas $\langle T\rangle$ and the total neutron radiation yield N_{DT} (Fig. 4), and also the double W and average density $\langle\rho\rangle$ (Fig. 5). The average density of the DT gas was determined by the equation $\langle\rho\rangle = \rho_{DT}r_2^2/r^2(t, s_{DT})$, and the average temperature from the equation of state of the DT gas by the average specific energy $\langle\varepsilon_T\rangle = 2\int_0^{s_{DT}} \varepsilon_T ds/(\rho_{DT}r_2^2)$.

The average temperature of the DT plasma reaches ~2 keV, while the double W of ~0.38 satisfies the criterion for reaching the ignition threshold Eq. (1).

At the time of maximum compression, the plasma radius is $r_{min} = 1.15 \times 10^{-3}$ cm (see Fig. 3). The corresponding range of the α particle calculated by Eq. (2) at average $\rho = \langle\rho\rangle$, $T = \langle T\rangle$ values (see Figs. 4 and 5), is $\lambda_\alpha \approx 5 \times 10^{-4}$ cm. Since r_{min} is more than twice as large as λ_α, when solving Eqs. (3), taking into account the thermonuclear energy release, we assume that all the released energy Eq. (5) remains at the point of birth of the α particle.

The comparison of the temperatures of the DT plasma and neutron radiation yield calculated taking into account and disregarding thermonuclear energy release is shown in Fig. 6a for voltage $U_0 = 5$ MV, and in Fig. 6b for voltage $U_0 = 7$ MV. Note that the current amplitude reaches ~220 MA at $U_0 = 7$ MV, the liner hits the target at the time of ~0.435 μs (cf. Fig. 3), and the electric energy entering the discharge is E_{el} ~ 400 MJ. In this case, the double reaches the value $W = 0.7$.

At $U_0 = 5$ MV, taking into account the thermonuclear energy release led to an increase in the DT plasma temperature (up to ~12%) and, accordingly, the neutron radiation yield increased by ~25%. The weak increase in the temperature and neutron yield is due to the fact that the system is at the ignition threshold. At $U_0 = 7$ MV, the temperature increase was up to ~25%, accordingly, the neutron radiation yield increased by ~70%.

It should be noted that the described scheme has a low conversion coefficient of the energy of the current source E_{el} into the energy of the generated neutron radiation: $\eta \approx 0.075\%$ for $U_0 = 5$ MV; $\eta \approx 0.15\%$ for $U_0 = 7$ MV. The burnout of DT fuel obtained in the calculations was $\chi \approx 0.15\%$ for $U_0 = 5$ MV; $\chi \approx 0.4\%$ for $U_0 = 7$ MV.

It follows from the dependence of double on the liner and target radii given in Table 1 at $U_0 = 5$ MV that its value is maximum for the case considered above $r_1 = 1.25$ cm, $r_2 = 0.025$ cm. That is, the selected parameters of the liner and target can be considered optimal for obtaining the maximum neutron yield.

The high convergence degree of the liner from 1.25 cm along the inner surface in the initial state to 1.15×10^{-3} cm along the outer surface of the target at

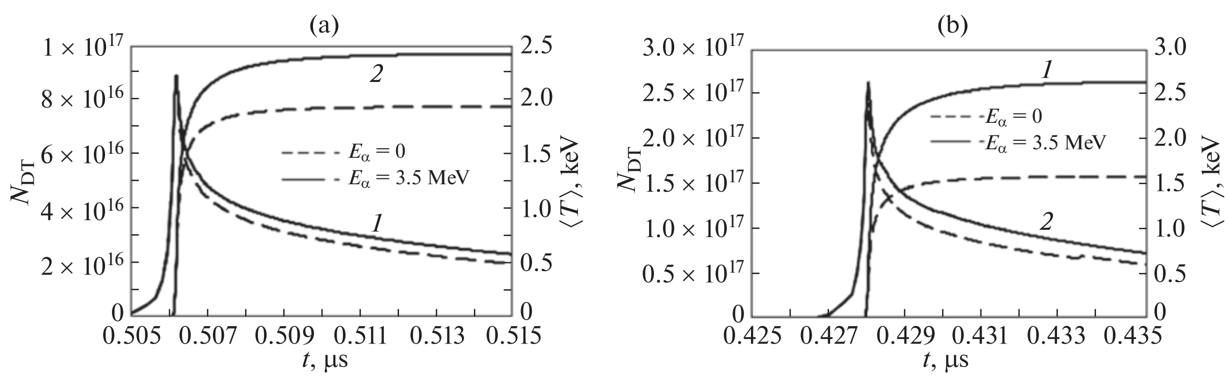

Fig. 6. Comparison of time dependences of (*1*) average temperature of the DT plasma $\langle T\rangle$ and (*2*) neutron radiation yield N_{DT} calculated taking into account and disregarding energy release of α particles: (a) $U_0 = 5$; (b) 7 MV.

Table 1. Dependence of the double W on radii of the liner r_1 and target r_2 at $U_0 = 5$ MV

r_2, cm	r_1, cm		
	1.0	1.25	1.5
0.0125		0.250	
0.025	0.352	0.380	0.375
0.050		0.36	

the time of maximum compression, i.e., ~1000 times along the radius is noteworthy. The instability develops on its outer surface at the liner acceleration stage (from the inner surface coordinate of 1.25 cm to 0.025 cm—compression of ~50 times along the radius). The practice of the experimental work shows that at the existing metalworking technology, the stability of the inner surface of the liner is ensured for the convergence of a radius of no more than 10 of its thickness. In our case of the initial liner thickness of 0.125 cm, this criterion is met. We hope to be able to achieve the required compression of ~20 along the radius of the DT plasma, since such compressions are achieved in many experiments with spherical and cylindrical targets.

4. CONCLUSIONS

The calculation analysis shows that modern technologies make it possible to hope for reaching the ignition threshold by heating the DT gas in a shock wave with its subsequent compression by a liner accelerated by a current pulse. The level of currents of ~200 MA required for this in time of ≤0.5 μs with a pulse energy of 300–400 MJ is fundamentally accessible by modern disk EMGs. However, in this case, relatively low conversion coefficients of the magnetic field energy into the thermonuclear neutron energy $\eta \approx 0.1\%$ and DT gas burnout $\chi \le 0.4\%$ are implemented, and, accordingly, neutron radiation yields of $N_{DT} \sim 10^{17}$ neutrons per pulse.

Previous studies using a similar calculation method have shown [20] that when compressing a magnetized DT plasma preheated by laser radiation to a temperature of ~250 eV in the geometry of the MagLIF project [15, 16] for the same time of ~0.5 μs, a lower energy of the current source of ~100 MJ is required to achieve the double $W = 0.35$–0.5. In this case, the conversion coefficient of the magnetic field energy into the thermonuclear neutron energy is $\eta \approx 60\%$, the burnout of DT gas is $\chi \sim 10\%$, and the corresponding neutron radiation yield N_{DT} is $\sim 10^{19}$ neutrons per pulse.

Thus, thermonuclear ignition using a liner accelerated by a pulsed current is possible both in the direct shock heating scheme with subsequent compression and in the compression scheme of the preheated DT plasma formulated in the MAGO/MTF projects and currently being developed in the MagLIF project. The first direction is simpler to implement. Its undoubted advantage is the use of a solid target, which allows avoiding a number of problems in experiments associated with the development of plasma instabilities and the influence of heavy element impurities. Second, the higher initial temperature and magnetization of the DT plasma, allows one to achieve significantly (more than in 100 times) higher efficiency in converting the field energy into the thermonuclear neutron energy, DT plasma burnout, and neutron radiation yield.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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