Impulse source of high energy neutrons emitted by fusion reactions after compression of D-T gas by cumulative detonation waves

V.D. Rusov*, V.A. Tarasov, S.A. Chernezhenko, V.P. Smolyar, V.V. Urbanovich, T.N. Zelentsova

Odessa National Polytechnic University,
Department of Theoretical and Experimental Nuclear Physics,
Shevchenko av. 1, 65044 Odessa, Ukraine

Abstract

We develop the physical model and the system of equations for the impulse neutron source (INS) of high-energy neutrons (∼ 14 MeV) emitted by fusion reactions during compression of D-T gas by cumulative detonation waves. The system of INS equations includes a system of gas dynamic equations that takes into account the energy transfer by radiation, equations for the radiation flux, the equation of the shock adiabat (the Hugoniot adiabat) for a compressed gas, and the equation for the neutron yield.

We perform the INS dynamics simulation for the spherical and cylindrical geometries, and calculate maximum temperatures of D-T plasma, its density and neutron yield in the pulse.

The obtained temperature estimates and simulation results show that the thermonuclear fusion temperatures are reached within this approach, and the fusion reactions proceed. Their yield determines the yield of neutrons.

1 Introduction

In a recent book by Kozyrev [1] it was proposed to conduct the research and development work (R&D), to develop a gas dynamic thermonuclear neutron source (GDTs). The Author suggested to initiate a thermonuclear fusion reaction $D(d,n)^3He$ by dynamically compressing a deuterium-deuterium (D-D) gas mixture with a spherical converging detonation wave (cumulative detonation wave), which would give rise to a neutron flux. Some estimates were also made, which justify the principal feasibility of such source of neutrons.

Such R&D work was apparently carried out, since the preface to [1] as well as [2–5] mention the experiment conducted in 1982 in VNIEF (Sarov, Russia) involving a device built on the basis of Kozyrev approach, using a liquid explosive (tetrynitromethane in nitrobenzene). The neutron yield was reported to reach $4 \cdot 10^{13}$ neutrons per pulse. According to [4], in this device a deuterium-tritium (D-T) gas with the initial radius of $r_0 = 1\,mm$ and initial density of $\rho_0 = 0.1\,g/cm^3$ underwent a compression. The temperature reached $T = 0.65\,keV$ ($T = 0.78 \cdot 10^7\,K$), and the maximum density $\rho_{\text{max}} = 80\,g/cm^3$.

Still, according to [4, 5], the yield of neutrons turned out to be 2-3 orders of magnitude lower than expected ($9.5 \cdot 10^{16}$). As noted in [4, 5], this deviation may be associated with

*Corresponding author e-mail: siiis@te.net.ua
asymmetry and mixing at the boundary of substances of different density, and increasing gas
dynamic instabilities in GDTS.

Let us note that the temperature of a thermonuclear plasma was apparently estimated by a
method described in [6]: the neutron spectrum was measured during the experiment, and the
temperature was calculated from the half-width of the neutron spectrum maximum.

In [7, 8] a phenomenon of the unlimited cumulation not related to a centripetal motion of
the gas (i.e. for a plane shock wave) was theoretically discovered. It was caused by a special
periodic structure of matter ("sandwich") along the shock wave path. Such motion is a periodic
self-similar process.

Here we present the estimates that also confirm the possibility of the impulse neutron source
(INS) implementation with the neutrons being emitted by fusion reactions $T(d, n)^4He$ during
the compression of the D-T gas by cumulative detonation waves. We also define the physical
model and a system of equations (gas dynamic and other necessary equations for the model)
for the INS. On the basis of this model we developed a computer software and conducted the
numerical simulations. Our simulation results demonstrate a good agreement with preliminary
estimates.

2 Estimation of the INS feasibility using D-T gas com-
pression by cumulative detonation waves

In order to substantiate the fundamental possibility of INS realization by the thermonuclear
fusion reactions $T(d, n)^4He$ under compression of D-T gas by cumulative detonation waves,
the following preliminary estimates may be given.

The attainable temperatures for the compression of a deuterium-tritium gas by spherical
convergent shock waves can be calculated within the framework of the Zel’dovich model [9].
It deals with the adiabatic compression of a gaseous medium by a running plane shock wave,
and gives the expressions for the maximum compression of a gas and for the dependence of its
temperature on the amplitude of a shock wave pressure:

$$\frac{V_0}{V_1} = \frac{\gamma + 1}{\gamma - 1},$$

$$\frac{T_1}{T_0} = \frac{\gamma - 1}{\gamma + 1} \cdot \frac{P_1}{P_0},$$

where $V_0$ is the initial volume, $V_1$ is the volume of the gas after compression, $\gamma$ is the adiabatic
index,

where $T_0, P_0$ are the initial temperature and pressure of the gas, $T_1$ is the maximum temperature
of the gas after its compression by a shock wave, and $P_1$ is the amplitude of the shock wave
pressure.

It was also shown in [9] that the gas compression is described by the Hugoniot state equa-
tion (shock adiabat), which depends on two parameters (e.g. $f(T, V, P)$, where $V$ and $P$ are
parameters) in contrast to the Clapeyron equation, which depends on a single parameter (e.g.
$f(T, V)$, where $V$ is a parameter).

So for the maximum temperature of the gas being compressed by a spherical convergent
shock wave, we obtain the following expression:

$$T_1 = c_{coll} \cdot c_{sph} \cdot \frac{\gamma - 1}{\gamma + 1} \cdot \frac{P_1}{P_0} \cdot T_0,$$

where $c_{sph}$ is the coefficient that takes into account the growth of the pressure amplitude in a
converging spherical shock wave and which, using (1), may be expressed as:
Figure 1: On the issue the single and multiple adiabatic compressions of a gas to the same pressure $P$ (where $H_A$, $H_B$, $H_C$ are the shock adiabats for which $A$, $B$ and $C$ are the initial points; $P$ is the Poisson adiabat) [9].

$$c_{sph} = \left( \frac{r_0}{r_1} \right)^2 = \left( \frac{V_0}{V_1} \right)^\frac{2}{3} = \left( \frac{\gamma + 1}{\gamma - 1} \right)^\frac{2}{3},$$

where $r_0$ is the initial radius of the gas having a spherical shape, $r_1$ is the minimum radius of the compressed gas, and $c_{coll}$ is the coefficient that takes into account the increase in the pressure amplitude in a convergent spherical shock wave caused by the collision of a converging spherical wave\(^1\), which, according to [1], can be chosen equal to 10.

It is well known that the maximum energy yield in an exothermic nuclear reaction is in the C-system. However, few researchers pay attention to the actual gain in the reaction energy when carried out in the C-system (e.g. in the collider) relative to the L-system (stationary target exposed to the particle beam). A good illustration of such gain is given in [10], which gives the minimum kinetic energy of colliding protons and antiprotons, necessary for the formation of the neutral bosons of a weak field ($Z^0$ bosons) in C-system and L-system. The minimum kinetic energy for the protons is 45.6 GeV for the C-system, and 4434.0 GeV for the L-system. So the gain in the energy of the reaction products is 100 times.

According to [1, p.56] and [11], when two shock waves with equal pressure amplitude collide ($N = 2$), $c_{coll} = 6$, and in the case of a converging spherical wave $N > 2$ and $c_{coll} = 10$.

According to [9], $\gamma = 5/3$ and the maximum compression is 4 for a monatomic gas, $\gamma = 7/5$ and the maximum compression is 6 for a diatomic gas with no excitations, and $\gamma = 9/7$ and the maximum compression is 8 for a diatomic gas with excitations.

Since the Hugoniot equation depends on two parameters, it is impossible to reach the same finite state of the gas by compressing with several shock waves and a single shock wave, starting from the same initial state [9]. For example, if a strong shock wave passes through a monoatomic gas, the gas will be compressed by four times. By contrast, if two consecutive strong shock waves (with the same final pressure) pass through the gas, it will be compressed by 16 times. This is demonstrated well in Fig. 1 from [9].

Let us remark that such compression of a gas by several consecutive spherical convergent shock waves is called a "cascade shock wave" by Kozyrev in [1].

\(^1\)An analogue of the increase in kinetic energy transformed into the energy of reaction products after the particles collision in the center-of-mass system (C-system) as compared to the reaction with a stationary target, i.e. in a laboratory system (L-system)
Table 1: Data from [1]

| Explosive  | Detonation velocity, m/s | Detonation density, g/sm³ | Detonation products density, g/sm³ | Detonation products pressure, P_D, atm | Pressure at reflection, P_R, atm |
|------------|--------------------------|---------------------------|----------------------------------|----------------------------------------|---------------------------------|
| PETN       | 7900                     | 1.60                      | 2.12                             | 250000                                 | 560000                          |
| Nitroglycerine | 7900                   | 1.60                      | 2.12                             | 250000                                 | 560000                          |
| Lead azide | 3890                     | 1.60                      | 2.12                             | 250000                                 | 560000                          |

Table 2: Calculated data for c_{coll} = 1

| Explosive  | Pressure P_1, atm | Single shock wave | Cascade of two shock waves | Monatomic gas, c_{sph} | Diatomic gas without excitations, c_{sph} | Diatomic gas with excitations, c_{sph} | Maximum temperature, 10^7 K |
|------------|------------------|-------------------|---------------------------|------------------------|-------------------------------------------|----------------------------------------|-----------------------------|
| PETN       | 250000           | ●                 |                           | 2.25                   | -                                         | -                                      | 4.22                        |
| PETN       | 250000           | ●                 |                           | 6.34                   | 3.30                                      | -                                      | 11.89                       |
| PETN       | 250000           | ●                 | 10.88                     | -                      | 3.99                                      | 3.89                                   |
| PETN       | 250000           | ●                 |                           | -                      | 15.96                                    | 15.56                                  |
| Lead azide | 400000           | ●                 |                           | 2.25                   | -                                         | -                                      | 6.75                        |
| Lead azide | 400000           | ●                 |                           | 6.34                   | 3.30                                      | -                                      | 19.02                       |
| Lead azide | 400000           | ●                 | 10.88                     | -                      | 3.99                                      | 3.99                                   |
| Lead azide | 400000           | ●                 |                           | -                      | 15.96                                    | 15.96                                  |

Table 3: Calculated data for c_{coll} = 2

| Explosive  | Pressure P_1, atm | Single shock wave | Cascade of two shock waves | Monatomic gas, c_{sph} | Diatomic gas without excitations, c_{sph} | Diatomic gas with excitations, c_{sph} | Maximum temperature, 10^7 K |
|------------|------------------|-------------------|---------------------------|------------------------|-------------------------------------------|----------------------------------------|-----------------------------|
| PETN       | 250000           | ●                 |                           | 2.25                   | -                                         | -                                      | 8.44                        |
| PETN       | 250000           | ●                 |                           | 6.34                   | 3.30                                      | -                                      | 23.78                       |
| PETN       | 250000           | ●                 | 10.88                     | -                      | 3.99                                      | 7.78                                   |
| PETN       | 250000           | ●                 |                           | -                      | 15.96                                    | 31.12                                  |
| Lead azide | 400000           | ●                 |                           | 2.25                   | -                                         | -                                      | 13.50                       |
| Lead azide | 400000           | ●                 |                           | 6.34                   | 3.30                                      | -                                      | 38.04                       |
| Lead azide | 400000           | ●                 |                           | -                      | 3.30                                      | 13.48                                  |
| Lead azide | 400000           | ●                 | 10.88                     | -                      | 3.99                                      | 44.38                                  |
| Lead azide | 400000           | ●                 |                           | -                      | 15.96                                    | 49.80                                  |

The data on the amplitudes of the pressure in shock waves are given in Table 1 for several classical powerful explosives (pentaerythritol tetranitrate (PETN), nitroglycerine, lead azide), and may be used for the estimations.

So using (3) for T_0 = 300 K, P_0 = 1 atm., we estimate the maximum temperatures. They are presented in Tables 2 and 3.

These estimates show that the thermonuclear temperatures may be reached.
3 Physical model of the INS and the simulation results

The physical model of the INS should include the heat transfer equation in addition to the hydrodynamic equations (gas dynamics).

Because of the high-speed processes in the INS (according to Table 1, the shock wave velocity is \( v \sim 6000-8000 \text{ m/s} \)), it is necessary to take into account the radiation energy losses. Indeed, a qualitative switch to the radiation energy transfer happens when the hydrodynamic and radiation energy fluxes become comparable [12], i.e. under the condition:

\[
\sigma T^4 / \rho v^3 \sim 1,
\]

where \( \sigma \) is the Stefan-Boltzmann constant, \( \rho \) is the medium density.

The system of gas dynamics equations for INS in the Euler representation (e.g. [9, 12]) is:

\[
\frac{\partial \rho}{\partial t} + \text{div} \left( \rho \vec{V} (\vec{r}, t) \right) = 0,
\]

\[
\frac{\partial \vec{V} (\vec{r}, t)}{\partial t} + (\vec{V} (\vec{r}, t) \text{div} \vec{V} (\vec{r}, t)) + \frac{1}{\rho} \nabla P (\vec{r}, t) = 0,
\]

\[
\frac{\partial \rho E}{\partial t} + \text{div} \left( \rho E \vec{V} \right) + \text{div} \left( P \vec{V} \right) + \rho Q - \text{div} \vec{S} = 0,
\]

where \( \rho \) is the medium density, \( \vec{V} \) is the mass velocity, \( E = \varepsilon + V^2/2 \) is the total energy density, and \( \varepsilon \) is its thermal component, \( P \) is the pressure, \( Q \) is the energy release per unit time (proportional to the fusion reaction rate in the compressed D-T plasma), \( \vec{S} \) is the radiation flux.

Equation for the radiation flux:

\[
\vec{S} (\vec{r}, t) = \int_0^\infty \vec{S}_\nu d\nu,
\]

where

\[
\vec{S}_\nu = \int_0^\infty I_\nu \vec{\Omega} d\Omega,
\]

\[
I_\nu \left( \vec{r}, \vec{\Omega}, t \right) = \hbar c f \left( \nu, \vec{r}, \vec{\Omega}, t \right) d\nu d\Omega,
\]

where \( \vec{\Omega} \) is the unit vector specifying the direction of the quanta propagation, \( \nu \) is the quanta frequency, \( c \) is the speed of light in vacuum, \( \hbar \) is the Planck constant, \( f \) is the frequency distribution function of the radiation intensity.

In order to specify the frequency distribution of the radiation intensity, let us use the Wien function, e.g. [13]:

\[
f_\nu = \frac{8 \pi \nu^3}{c^3} \exp \left( -\hbar 2\pi \nu / kT \right).
\]

To complete the problem, it is necessary to introduce the equation of state for the compressed D-T gas. We use the shock adiabat (Hugoniot equation) for this purpose [9, 14, 15]:

\[
P_1 = H \left( V_1, P_0, V_0 \right),
\]
which may be expressed explicitly when the thermodynamic relations \( \varepsilon (P,V) \) or \( \varepsilon (P,\rho) \) are expressed in simple equations. Let us note that the thermodynamic properties of the system are assumed to be known in our problem.

For example, according to [9], the Hugoniot equation for an ideal gas with a constant heat capacity has the following form:

\[
P_1 = \frac{(\gamma + 1) V_0 - (\gamma - 1) V_i}{(\gamma + 1) V_i - (\gamma - 1) V_0} P_0, \tag{14}
\]

and the ratio of the volumes and temperatures:

\[
\frac{V_1}{V_0} = \frac{(\gamma - 1) P_1 + (\gamma + 1) P_0}{(\gamma + 1) P_1 + (\gamma - 1) P_0}, \tag{15}
\]

\[
\frac{T_1}{T_0} = \frac{P_1 V_1}{P_0 V_0}. \tag{16}
\]

We solved the system of gas dynamics equations for INS ((6)-(8)) with respect to unknown \( P \), \( \rho \) and \( \vec{V} \) numerically. For this purpose we applied the particle-in-cell method [16]. The radiation transfer equations in the multigroup approximation were solved using the \( S_n \)-method [17].

We tested this scheme by comparing the simulated deuterium compression to the experimental \( P-\rho \) diagram for deuterium [14, 15].

The neutron yield is equal to the yield of the thermonuclear fusion reaction \( T(d,n) ^4 \)He, and was calculated as follows:

\[
\varphi = \int_{t_s}^{t_f} \hat{\rho} \langle v\sigma \rangle dt, \tag{17}
\]

where \( \hat{\rho} \) is the density of the plasma particles, \( \langle v\sigma \rangle \) is the fusion reaction cross section averaged over the velocities of the thermal motion of the particles. According to [18], it was given as:

\[
\langle v\sigma \rangle = \text{Const} \cdot \theta^{-\frac{3}{2}} \exp \left[ -3 \left( \frac{\pi e^2}{\bar{h}c} \right)^{\frac{3}{2}} \left( \frac{mc^2}{2\theta} \right)^{\frac{1}{2}} \right], \tag{18}
\]

where \( \text{Const} = 2^{5/6} \cdot 3^{-1/2} \cdot \frac{2\pi e^2}{\bar{h}c} \cdot m^{-1/3} \cdot \theta = kT \), \( m \) is the reduced mass of the interacting nuclides D and T, \( e \) is the elementary charge, \( t_s \) is the time of the fusion reactions start (the moment when the thermonuclear temperatures are reached in the compressed D-T plasma), \( t_f \) is the fusion reactions end time (determined as the moment when the mass velocity becomes zero).

We simulated spherical (Fig. 2) and cylindrical (Fig. 3) INS.

We performed the simulation of the INS with a single explosive layer, as well as a ”sandwich” structure of interlaced explosive (lead azide, \( \rho = 4.7 \text{ g/cm}^3 \)) and Polymethylpentene (\( \rho = 0.8 \text{ g/cm}^3 \)) layers. One mole of D-T gas (\( \rho = 0.1 \text{ g/cm}^3 \)) was compressed, and the mass of the explosive was \( \sim 500 \text{ kg} \). The spherical INS simulation demonstrated the maximum temperature of \( 2 \cdot 10^8 \) K, the maximum density \( \rho_{\text{max}} = 1.6 \text{ g/cm}^3 \), and the neutron yield of \( 9.4 \cdot 10^{17} \) per pulse (neutron energy \( \sim 14 \text{ MeV} \)). The cylindrical INS demonstrated the maximum temperature of \( 1.3 \cdot 10^8 \) K, the maximum density \( \rho_{\text{max}} = 1.2 \text{ g/cm}^3 \) and the neutron yield of \( 6.7 \cdot 10^{16} \) per pulse.
4 Conclusions

We developed a physical model and a system of equations for the impulse high-energy neutron source (INS) (neutron energies $\sim 14$ MeV). The neutrons are emitted by fusion reactions during compression of a D-T gas by cumulative detonation waves. The system of equations for the INS includes: the system of gas dynamic equations that takes into account the radiation energy transfer; the equations for the radiation flux; the equation of the shock adiabat (Hugoniot adiabat) for a compressed gas; the equation for the neutron yield.

We performed the simulation of INS dynamics for spherical and cylindrical geometries and estimated the maximum temperatures of D-T plasma, its density and neutron yield per pulse. The obtained estimates and simulation results show that on the basis of this approach, the thermonuclear fusion temperatures are reached, and a fusion reaction proceeds. The yield of this reaction determines the neutron yield.

It should be noted that the feasibility of INS is also confirmed by the published experimental results [1–5]. The deviation of the experimental results from the idealized calculated neutron yields in [1–5] may be related to the following reasons.

The problem of asymmetry of a convergent spherical shock wave: a complex system of fuses was used to initiate the blast wave from the explosive surface. The shock wave asymmetry could be caused by the discrete zones of the fuses, and by the errors in the electronic fuse synchronizer.

The small neutron yield can also be associated with the small amount of D-T mixture (only 0.1 g) and insufficient amount of explosive (there is no data on the amount of explosive in
the experimental device in [1–5]). The neutron yield is determined by the number of fusion reactions. As shown in [1], this number is determined by the ratio of the fusion reaction initialization time $t_{fusion}$ in compressed D-T mixture and the time of its inertial compression $t_{in}$. After the inertial compression time $t_{in}$, starting from the point of maximum compression, the compressed mixture begins to expand, i.e. scatter in the opposite direction. So for a significant yield of neutrons, it is necessary to fulfill the condition $t_{fusion} \leq t_{in}$. And the time of inertial compression $t_{in}$ depends on the mass of the compressed gas and the explosive in the device. The mass of explosive in turn depends on the density of the explosive.

As also shown in [1], the neutron yield depends on the maximum degree of compression, since the initialization time of the fusion reaction $t_{fusion}$ depends on the compression ratio exponentially, and sharply decreases with its increase (according to the estimate in [1], the 10% increase in the maximum compression decreases $t_{fusion}$ by two orders of magnitude). The maximum degree of compression may be increased using a cascade of two shock waves.

In order to increase the yield of neutrons and optimize the geometric parameters and weight of the INS, the R & D work should focus on the following:

a) the compression of the D-T mixture must be realized by means of a cascade shock wave or an interlaced (“sandwich”) explosive medium;

b) the synchronization of the shock wave initiation from the surface of an explosive layer can nowadays be implemented using a laser radiation with a given wavelength and the explosive sensitive to such radiation [19–26]. This would also solve the problem of the converging shock wave asymmetry and thus increase its stability;

c) in order to reduce the radiation losses, it is possible to add some heavy elements to the composition of the explosives and gas mixture – as the passive admixtures. The heavy metal salts, organometallic compounds, as well as the lead azide, mercury fulminate and other explosives containing heavy elements. It is also possible to inject the heavy elements into the gas mixture (like the mercury vapor), or to blow up a small charge of lead azide at the center at the moment of explosion, or to evaporate a small amount of metal by explosion [1];

d) in order to increase the neutron yield, it is necessary to increase the amount of reacting deuterium and tritium. For this purpose it is possible to use the explosives in which hydrogen is chemically replaced by deuterium and tritium (for example, if one uses the tetrynitromethane mixture in nitrobenzene solution, as in experiment [1–5], a heavy nitrobenzene may be used instead of the usual nitrobenzene). The products of such explosion, which forms the detonation wave, will contain deuterium and tritium, which will also take part in the fusion reaction [1].

In conclusion, let us note that the method [6] used to estimate the temperature of the thermonuclear plasma in the experiment [2–5] is based on the “Brysk Gaussian” [6], which determines the neutron energy distribution and does not take into account the moderation of neutrons in the medium. So this method may require some further improvement, in particular, by the recent neutron moderation theory [27].

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