

Article

Evaluation of Plasma Dynamic Parameters of a Multi-Layer MIF Target Under Exposure to External Broadband Radiation

Victor V. Kuzenov , Sergei V. Ryzhkov *  and Artem G. Polyanskiy

Power Engineering Faculty, Bauman Moscow State Technical University, Moscow 105005, Russia; kuzenov@bmstu.ru (V.V.K.); polyanskiyag@student.bmstu.ru (A.G.P.)

* Correspondence: svryzhkov@bmstu.ru; Tel.: +7-(499)-263-6570

Abstract

This work presents a numerical investigation into broadband radiation effects (with energy flux densities $q < 10^{14} \text{ W/cm}^2$) on a magneto–inertial fusion (MIF) target. The calculation results demonstrate the impact of intense energy fluxes on a multi-layer cylindrical target that provides more uniform and homogeneous compression. All principal dynamic parameters (plasma dynamics and radiative) of the compressed target plasma have been determined. The work performed allows us to draw the following initial conclusion: it is advisable to create compact neutron generators based on the MIF scheme on a multi-layer version of the target (made of “heavy” chemical elements).

Keywords: high-temperature plasma; magnetized target; broadband radiation; mathematical modeling; plasma dynamic processes

1. Introduction

Typically, the MIF scheme [1–4] achieves compression and heating of the plasma formation by high-speed plasma jets or high-power laser radiation. In this paper, the effect of external broadband radiation on a cylindrical target is studied numerically.

The pulsed radiation source (a Hohlraum design variant) comprises conical cavities embedded within a high-density solid material. Each conical cavity (exposed to external laser radiation) contains gaseous deuterium or its mixture with tritium. The D-T gas is confined within either a flat thin-walled shell or a convex membrane. When interacting with concentrated energy flux (laser beams), the shell implodes into the cavity at supersonic velocity, compressing and heating the D-T fuel. The plasma compression in the conical section of the radiation source can generate intense axis-aligned broadband radiation ($q = \sigma T^4 \sim 10^{16}–10^{20} \text{ W/cm}^2$). In this configuration, the initial laser radiation ($q_L \sim 10^{14} \text{ W/cm}^2$) may be amplified by up to 100 times (or more) through thermonuclear burning of the D-T mixture within the conical cavity.

The process of interaction between external broadband radiation and the target can be evolutionarily described as follows: After the initial heating of the target wall material by a strong shock wave (generated by heating the target with external broadband radiation), it accelerates and moves towards the center of symmetry of the target. When the center of symmetry of the fuel-containing target layers is reached, they accumulate (up to the stage of nuclear reactions). The cumulation along the system’s geometric axis compresses the plasma to the stage of nuclear reactions, where the reaction probability is proportional to $\exp(-KZ_1Z_2/\sqrt{E})$; here, Z_1, Z_2 are the proton numbers of the interacting nuclei, E is their relative approach energy, and K is a plasma-specific scaling factor in the target.



Academic Editor: Simone Minucci

Received: 23 September 2025

Revised: 7 October 2025

Accepted: 16 October 2025

Published: 17 October 2025

Citation: Kuzenov, V.V.; Ryzhkov, S.V.; Polyanskiy, A.G. Evaluation of Plasma Dynamic Parameters of a Multi-Layer MIF Target Under Exposure to External Broadband Radiation. *Appl. Sci.* **2025**, *15*, 11155. <https://doi.org/10.3390/app152011155>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Addressing this complex scientific–technical challenge requires the concurrent refinement of both plasma–physical models for targets and numerical methods to obtain its solution. Notably, such mathematical models may also enable the evaluation of physico–technical parameters for compact generators with practical applications, particularly those capable of producing intense, long-lifetime sources of high-energy particles (ions, neutrons).

The following is a brief description of the mathematical model used in the work; a variant of the author’s numerical methodology is indicated, and in Section 3 some of the results obtained in the work are analyzed. The conclusion is given at the end of the paper.

2. Mathematical Model and Computational Algorithm

In its full formulation—a multidimensional, multivelocity, multitemperature problem accounting for numerous possible physicochemical processes—this represents an exceptionally challenging computational task, even for modern high-performance computing systems.

However, the problem under consideration can be investigated using magnetohydrodynamic (MHD) models. This approach requires several simplifying assumptions, of which we highlight the following key ones:

- We will assume that plasma formation (monatomic plasma composition) consists of dissociated neutral and ionized gas. The mathematical description of the dynamics of such a plasma formation is based on a multi-liquid (single-velocity), high-temperature, chemically non-reactive continuous plasma medium.
- The calculation of dynamic processes (absorption and scattering) related to the solution of the Vlasov (or Fokker–Planck) kinetic equation for relativistic “suprathermal” electrons in a magnetic field is not considered.
- At the initial time, the plasma formation and the surrounding medium can be differentiated by specifying distinct thermodynamic parameters, as well as the degree of ionization $\alpha = n_e/n$, where n_e and n are the electron and heavy particle concentrations, respectively.

Assuming that the energy input by broadband radiation is cylindrically symmetrical and the wall of the multi-layer cylindrical target is thin, we will proceed with a one-dimensional mathematical model describing compression and energy release processes in the target. This mathematical model is based on the equations of radiation plasma dynamics, which take into account a self-sustaining thermonuclear fusion reaction. The governing equations are formulated in a spherically symmetric coordinate system and include the following:

$$\partial \rho / \partial t + \operatorname{div}(\rho u) = 0, \quad (1)$$

$$\partial(\rho u) / \partial t + \operatorname{div}(\rho u^2 + P) = f_r, \quad f_r = \frac{1}{c} \left[\vec{j} \times \vec{H} \right]_r,$$

$$\partial(\rho E) / \partial t + \operatorname{div}(\rho E u + P u + q_\Sigma) = q_r + Q_{Fus}^e,$$

$$\partial \rho e_e / \partial t + \operatorname{div}(\rho e_e u + P_e u + q + q_e) = q_r - Q_{ei} + Q_{Fus}^e,$$

$$q_r = j_r E_r + j_z E_z q_\Sigma = q_e + q_i + q, \quad P = P_e + P_i,$$

where the index $v = (1, 2, 3)$ corresponds to cases of planar, axial, and spherical symmetry, and q_{term} is the density of the external broadband radiation flux directed perpendicular to the generatrix of the multi-layer cylindrical target.

The fictitious impurity method is used to determine the spatiotemporal position of the contact boundary separating the plasma of the D–T mixture from the plasma of metals (Al, Au) or the environment. To do this, several additional equations are introduced into the system of the above equations ($\rho_g \in [0, 1]$) of the form $\partial \rho_g / \partial t + u \partial \rho_g / \partial r = 0$. Knowing ρ_g , it is possible to determine the position of the contact boundary $\Gamma(t) = \{\xi: \rho_g(\xi, t) = 0\}$, which

divides the entire computational domain into several regions, each of which corresponds to a D-T mixture, metal (Al) plasma, or the environment, depending on the sign of the function ρ_g .

Broadband radiation is calculated using a multigroup diffusion approximation [5,6]:

$$\text{div}(q_v) + \chi_v c U_v = \chi_v 4\sigma T^4, \quad -\frac{c}{3} \nabla U_v + \chi_v q_v = 0.$$

If the electron and ion distribution functions are Maxwellian, the energy transferred per unit time per unit volume from electrons to ions can be calculated by the formula

$$Q_{ei} = \sum_{k=1}^s f_k \frac{2m_e}{M_k} \frac{3}{2} k (T_e - T_{i,k}) v_{ei,k} n_e.$$

Here, $v_{ei,k}$ is the average frequency of electron–ion collisions with momentum transfer, given by the following [7]:

$$v_{ei,k} = \frac{4\sqrt{2\pi} n_k Z_{i,k}^2 e^4 \ln \Lambda_{ei}}{3m_e^{1/2} (kT_e)^{3/2}}, \quad \tau_{ei} = \frac{1}{v_{ei}} \cdot \frac{(1 + \theta)}{8},$$

where $E_F = \left(\frac{h^2}{2m_e}\right) (3\pi^2 n_e)^{\frac{2}{3}}$ is the Fermi degenerate energy, and $\theta = \exp\left(-\frac{E_F}{kT_e}\right)$ is the plasma degeneracy parameter that describes, in particular, the limiting cases of classical ($\theta \gg 1$) and fully degenerate ($\theta = 0$) plasma.

The developed numerical methodology has been verified through solutions to a series of test (model) problems [6–14].

3. Calculation Results

The computational domain and MIF target (Figure 1) consist of a central part and two coaxial layers (Al and Au). The computational domain has an outer radius 0.3 cm.

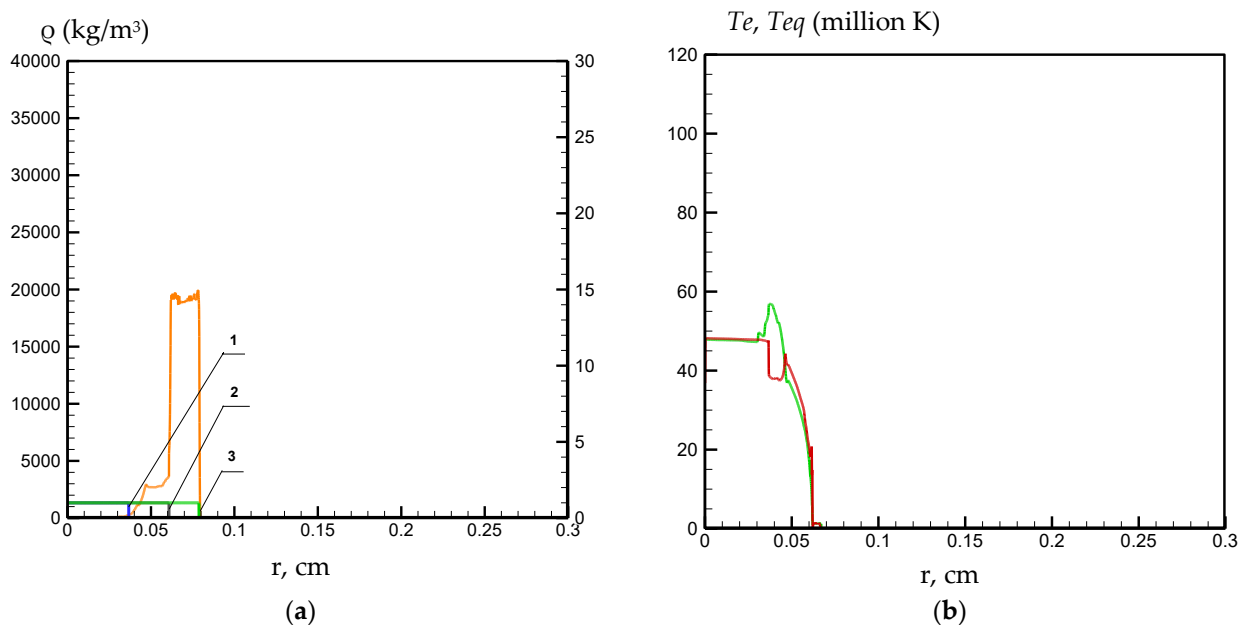


Figure 1. Spatial distribution (multi-layer case Al–Au): (a) density (orange line), ρ (kg/m³) and (b) average plasma temperature Teq (green line) and electron temperature Te (red line) at the time moment $t = 0.78$ ns. Positions of the contact boundaries (green line in (a)): 1 between D-T and Al; 2 between Al and Au, and 3 between Au and air.

Derivatives of the species $\partial T/\partial z, \partial \ln(n_e)/\partial z$ are determined along the forming multi-layer cylindrical target [15].

Then, the spatial region r_f^{nucl} and the velocity V_f^{nucl} of the thermonuclear reaction (propagation of the “thermal wave”) are estimated as $r_f^{nucl} = \sqrt{\chi \tau_{nucl}}$, $V_f^{nucl} = \frac{1}{2} \sqrt{\chi/\tau_{nucl}}$. Here, τ_{nucl} is the characteristic time of thermonuclear burning, $\tau_{nucl} = \frac{M_i}{\rho} \cdot \frac{1}{\langle V \sigma \rangle}$, where ρ is the current charge density, M_i is the mass of the ion participating in the thermonuclear reaction, V is the relative velocity of interacting nuclei participating in the thermonuclear reaction, and σ is the cross-section of the thermonuclear reaction.

The propagation velocity of the “photodetonation” wave V_D can be found from the relation $V_D = \sqrt[1/3]{2(\gamma^2 - 1) \frac{q}{\rho_0}}$, where ρ_0 is the medium density ahead of the photodetonation wave front [14]. Assuming equality ($q \approx P_f r_f^{nucl}$ —ignition by a “light-detonation” wave) of energy releases in the “light-detonation” wave q and in the region of the self-sustaining thermonuclear reaction $P_f r_f^{nucl}$, one can obtain the following estimate for the velocity of the thermonuclear reaction propagating in the “photodetonation” regime:

$V_D^{nucl} = \sqrt[1/3]{2(\gamma^2 - 1) \frac{P_f r_f^{nucl}}{\rho_0}}$, where $P_f = n_a n_b \langle \sigma V_{a,b} \rangle E_f$ is the fusion power per unit volume, $n_a n_b$ are the volume concentrations of reacting particles of the variety a, b ; $\langle \sigma V_{a,b} \rangle$ is the activity, the product of the reaction cross-section and the average particle velocity in the Maxwell distribution; and E_f is the energy of the thermonuclear reaction.

The expression for the specific power of bremsstrahlung radiation [6] is $Q = 1.5 \times 10^{-27} n_e n_i Z^2 \sqrt{T_e}$ [erg/(s·cm³)], where Z is the charge number of the ion of the element; n_e, n_i is the electron and ion concentration, cm³; and T_e is the electron plasma temperature, K. It follows from this ratio (all other things being equal) that the power Q_{Au} of the “braking” radiation at the contact boundary (Figures 2 and 3) from Au to Al is approximately 32 times greater, and from Al to D-T by 42 times.

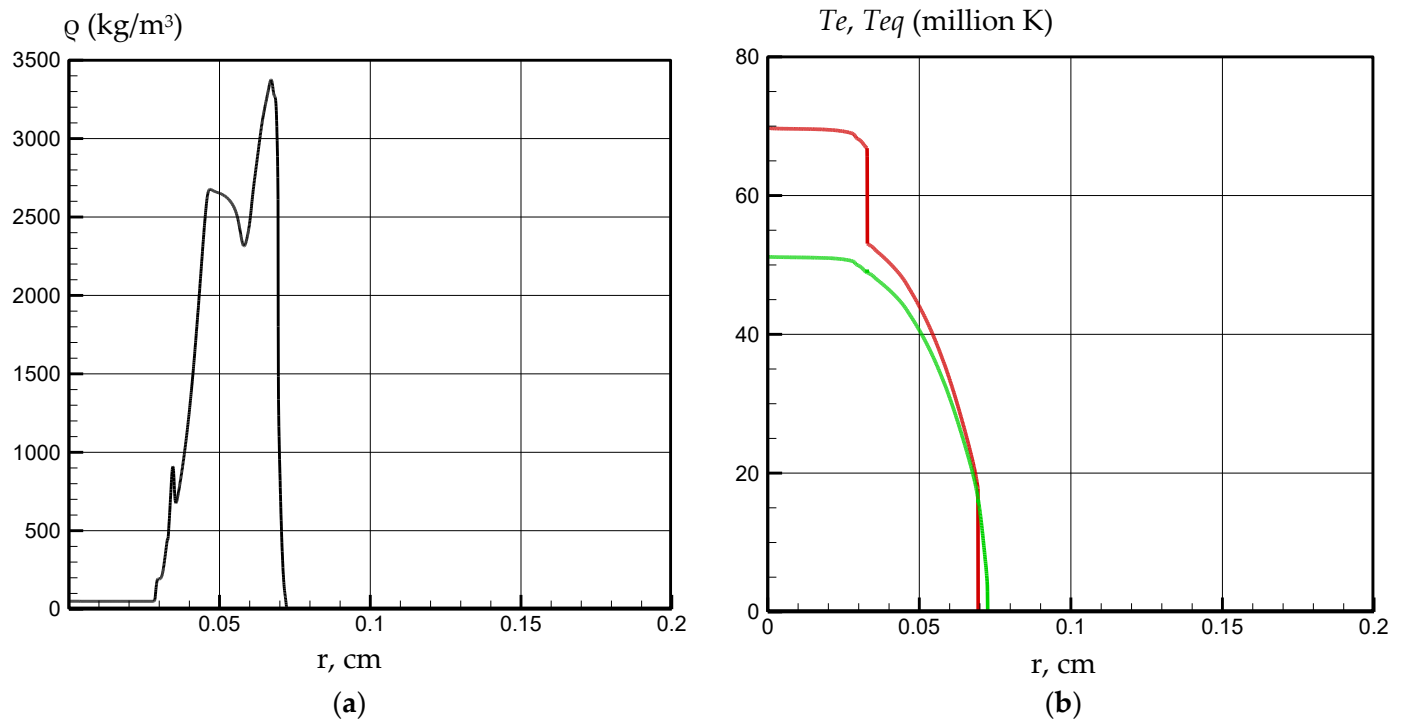


Figure 2. Spatial distribution (single-layer case: Al): (a) density, ρ (kg/m³) and (b) average plasma temperature Teq (green line) and electron temperature Te (red line) at time moment $t = 0.4$ ns.

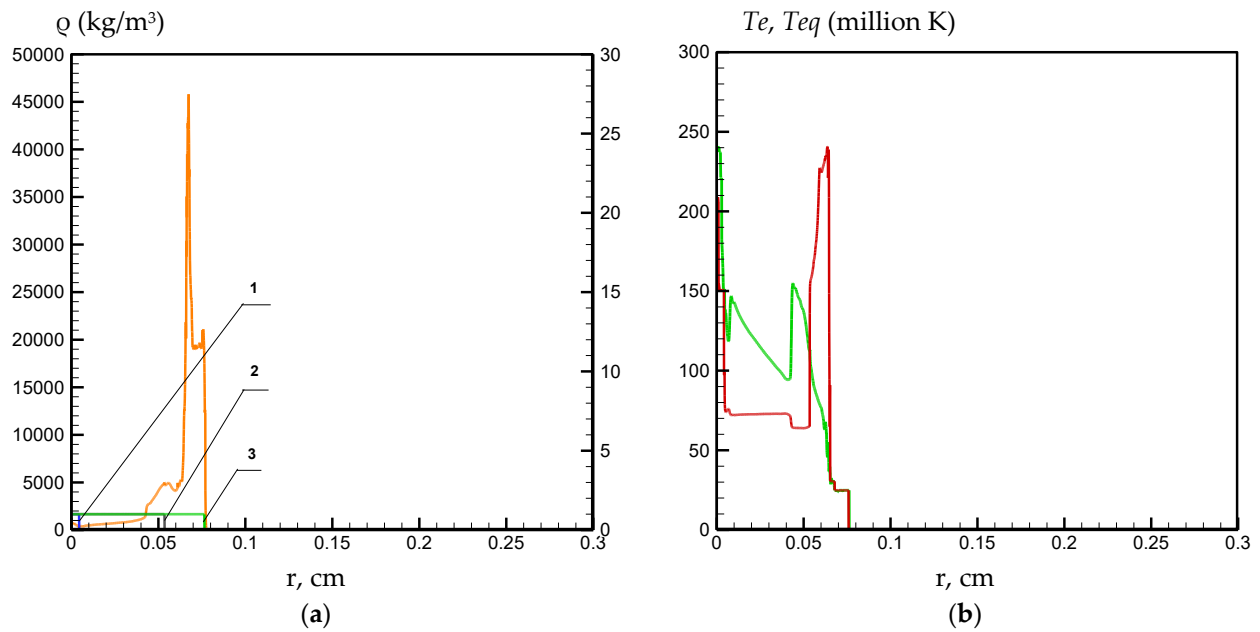


Figure 3. Spatial distribution (multi-layer case Al–Au): (a) density (orange line), ρ (kg/m³) and (b) average plasma temperature Teq (green line) and electron temperature Te (red line) at time moment $t = 1.03$ ns. Positions of contact boundaries (green line in Figures 1a and 3a): 1 between D-T and Al, 2 between Al and Au, and 3 between Au and air.

The process of compression (relative to time t) of the target by a system of pulsed broadband radiators (a variant of the Holraum design) can be described as having several spatial structural phases [15] (the main phases are the “collapse”, “re-reflection”, and “expansion” of the compressed and heated plasma).

Using the graphical dependencies shown in Figures 1–4, the paper describes the most interesting phases of “collapse” (Figures 1 and 2) and “re-reflections” (Figures 3 and 4).

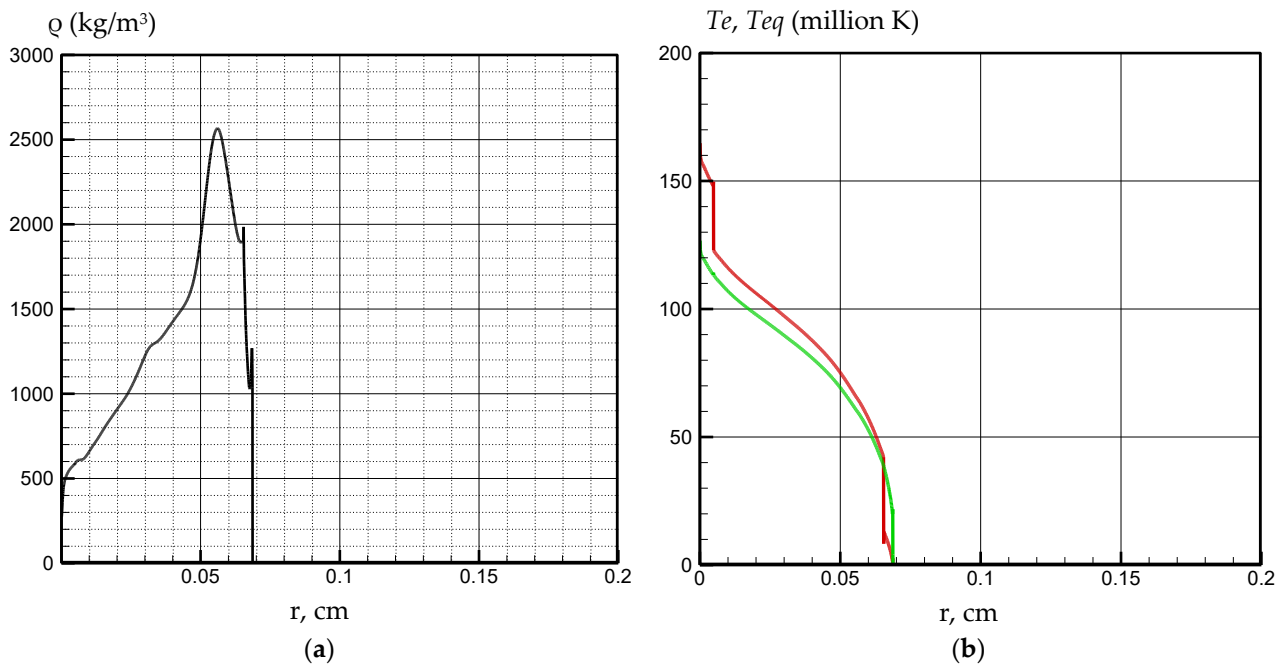


Figure 4. Spatial distribution (single-layer case: Al): (a) density, ρ (kg/m³) and (b) average plasma temperature Teq (green line) and electron temperature Te (red line) at time moment $t = 0.62$ ns.

The initial phase lasts for a time interval of $0 \leq t \leq 0.78$ ns (multi-layer case of Al–Au) and $0 \leq t \leq 0.4$ ns (single-layer case: Al).

The “collapse” phase (Figures 1 and 2) depends on the number of layers and target material, and lasts for the following time intervals, approximately: $0.78 \leq t \leq 1.03$ ns for the multi-layer case (Figure 1; Al–Au) and $0.4 \leq t \leq 0.61$ ns for the single-layer case (Figure 2; Al only). In the multi-layer case (note that the atomic mass of aluminum is 2.7 g/cm^3 , and for gold it is 19.25 g/cm^3), a later convergence of the spatial region occupied by the “thermal wave” (thermal wave velocity approximately corresponds to the electron temperature front velocity in the multi-layer target) with the system’s geometric symmetry axis is observed. In Figure 1, at distance $r = 0.04$ cm (from the symmetry axis), a shock wave is observed, behind the front of which there is a weak ($T - T_{eq} \sim 0.6$ million K) temperature stratification $T_e > T_{eq}$. Note (Figure 2) that, in the single-layer case, the temperature stratification T_e, T_{eq} is more significant (~ 40 million K).

The flow structure (Figure 2) observed in the single-layer case (the “collapse” phase) consists of a “heat wave”, and the formation of a shock wave (in this case, the front of the “heat wave” and the front of the shock wave coincide and are located in the area $r = 0.075$ cm) in the substance is observed in the time interval $0.4 \leq t \leq 0.61$ ns.

Figure 3 shows the spatial distribution (multi-layer case Al–Au) of density ρ and average plasma temperature T_{eq} in the MIF target at the “rebound” phase. In this case, multiple transition regions are present. The most important of these are noted as follows: the first shock wave (SW) front is located near the target symmetry axis, and the second SW front is at a distance from the axis. In the region $0.05 \leq r \leq 0.06$ cm, a significant separation of the average plasma temperature T_{eq} (b) (green line) and electron temperature T_e (red line) is observed. It can also be noted that the maximum temperature value is located in the region $T \approx 240\text{--}260$ million K, which significantly exceeds the maximum temperature level of the single-layer case.

Figure 4 shows the spatial distributions in a single-layer target resulting from intense broadband radiation exposure during the “recompression” phase. By this time, the maximum temperature T and pressure P are located on the geometric axis of the target and reach values of $T \approx 150$ million K (slight separation between ion and electron temperatures is observed), $P \approx 8 \times 10^9$ atm. However, the maximum density $\rho = 2.5 \times 10^3 \text{ kg/m}^3$ (where the magnetic pressure of the spontaneous field has a relatively high value of $P = 4.5 \times 10^4$ atm) is not on the target axis, but in the region of $0.06 \leq r \leq 0.075$ cm of the most intense broadband radiation absorption.

The simplified physical picture (Figure 4) of the thermophysical processes occurring in the flow interaction region is as follows: after the cumulative reflection ($T \approx 150$ million K) of plasma from the target axis, it rapidly expands ($u = 600$ km/s) with shock wave generation in the peripheral region.

As seen in Figures 1–4, the situation described may exhibit a spatial state (for relatively short time intervals $\Delta t < 0.1$ ns) where the following relation holds: $|\partial(q + q_e)/\partial r| > |Q_{ei}|$. In this spatial region, “supercooled” or “superheated” plasma [16] may form, which can be in a thermodynamically nonequilibrium ($T_e \neq T_{eq}$ and $Z_{cp} \neq \bar{Z}_{cp}$) state. Here Z_{cp} is the “nonequilibrium” average charge of heavy particles, $\bar{Z}_{cp}(n_e, T_e)$ is the equilibrium average charge of heavy particles, and T_{eq} is the effective temperature that would correspond to the actual equilibrium average charge $\bar{Z}_{cp}$ of heavy particles under thermodynamic equilibrium conditions.

As noted in [16], in cases where the plasma ionization state is primarily determined by collisions, one can classify (based on parameters existing at time t) the plasma state by the deviation in its heavy particles’ average charge Z_{cp} from the thermodynamic equilibrium value $\bar{Z}_{cp}(n_e, T_e)$. When $Z_{cp} > \bar{Z}_{cp}$, the predominant ions in the given spatial region

mainly recombine, while when $Z_{cp} \leq \bar{Z}_{cp}$, electrons primarily ionize and excite ions. We also note that at high ionization degrees $Z_{cp} > \bar{Z}_{cp}$, the plasma is “supercooled”, and $T_e < T_{eq}$, whereas at low ionization degrees $Z_{cp} \leq \bar{Z}_{cp}$, the plasma is “superheated”, and $T_e \geq T_{eq}$. This observed temperature “stratification” (in the considered case near shock wave fronts) is shown in Figures 1–4 and occurs during both the “implosion” and “recompression” phases.

Overall, the behavior [16] of electron and ion temperatures in the transition region near the shock (detonation) wave front (Figures 1–4) can be qualitatively described by the following main physical mechanisms (accounting for e - i exchange): conductive heating of electrons ahead of the shock front; non-adiabatic heating of electrons behind the shock front; and collisional heat exchange (both ahead and behind the shock front) between electrons and ions. The inclusion of thermal conductivity (particularly “radiative” conductivity [6]) leads to the formation of an electron-gas-heating “tongue” ahead of the shock jump, causing greater increase in T_e than would occur with adiabatic heating. Collisional e - i exchange results in an overall electron temperature increase behind the shock front.

The number of neutrons N_{fus} can reach levels of 10^{15} n/cm (for the single-layer case, Al) and 35×10^{15} n/cm (for the multi-layer case, Al–Au) (Figure 5).

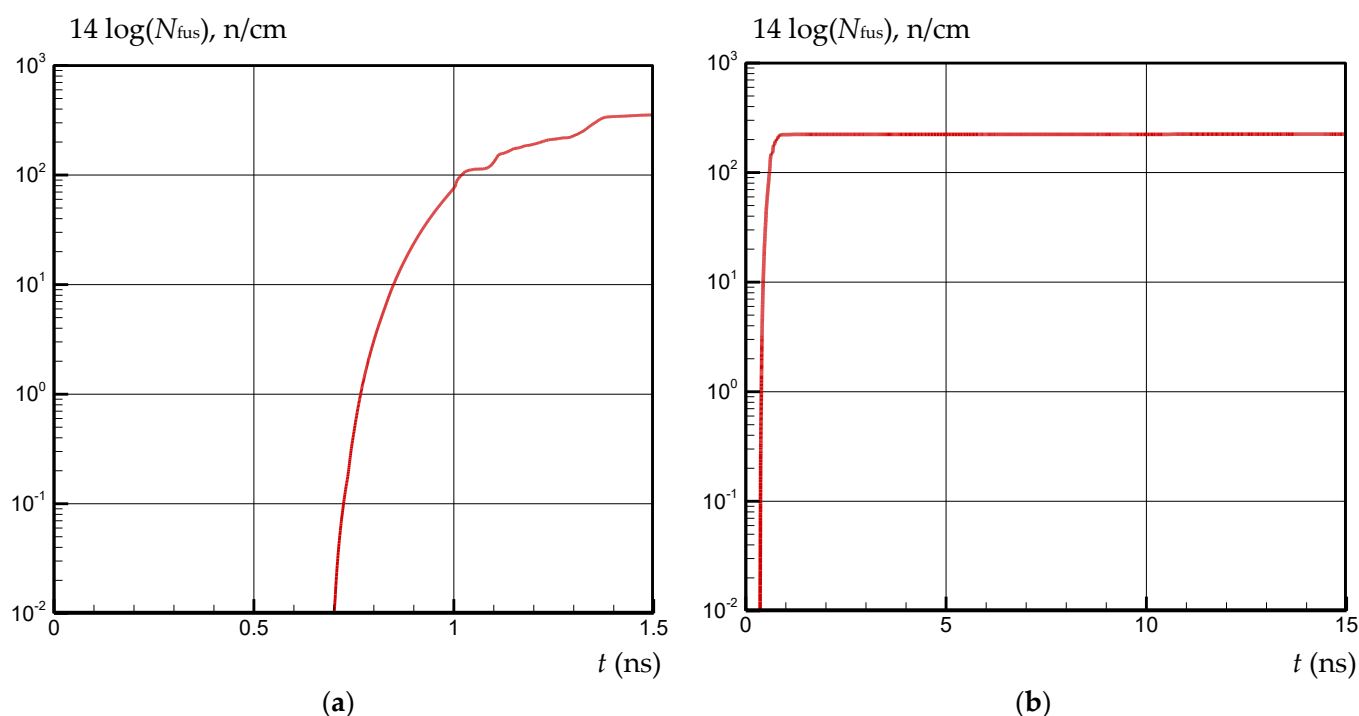


Figure 5. The number of neutrons N_{fus} (n/cm) that have left the computational domain by time t : (a) multi-layer case Al–Au and (b) single-layer case: Al.

We should note that regardless of the chosen target type (single-layer or multi-layer) hydrodynamic instabilities (not accounted for in these calculations) may develop during compression and prevent the achievement of optimal thermonuclear fuel parameters. It should be noted that, for the more accurate calculation of neutron numbers, accounting for mixing of the target material is required. Broadband lasers for fusion experiments have been discussed recently in other works [17–19]. Applications of wideband pulses and plasma jets in an external magnetic field have been studied experimentally and theoretically in papers [20–25].

4. Conclusions

The paper evaluates the plasma dynamic parameters of a single-layer and multi-layer cylindrical target under the influence of intense broadband radiation fluxes. During the calculations, a new version (developed by the authors of the article) of the numerical solution method for one-dimensional plasma dynamic equations was used. This method is based (for the “hyperbolic” part of the system for Equation (1)) on a nonlinear quasi-monotonic compact polynomial difference scheme of an increased order of accuracy, and for the “parabolic” part of the system of equations, a new (it allows calculations in cases of intense discontinuities in transport coefficients) numerical method is used to solve the magnetic field diffusion equation and the heat equation using a monotonized difference scheme of an increased order of accuracy.

All stages of compression of the target have been analyzed and it is shown that the temperature of the central part of the target can reach the level of $T > 200$ million K. The possibility of creating neutron generators (the number of neutrons per unit length $N_{fus} = 1.0 \times 10^{17}$ n/cm by the time of the end of exposure for a multi-layer target) using external broadband radiation is shown at certain points in time (Figure 5). The 1D calculations of the plasma dynamic parameters of the cylindrical target take into account a wide range of physical effects and generally provide information about the dynamics of processes in areas of the 3D target where the study density is either at its most intense or relatively low., i.e., 1D calculations in principle (without taking into account mutual influence) allow us to obtain pictures of 2D distributions of absorbed energy, plasma dynamic and thermodynamic quantities, and therefore judge the operability of the neutron generator circuit based on the effect of broadband radiation on the target.

Author Contributions: Conceptualization, S.V.R. and V.V.K.; data curation, V.V.K.; formal analysis, S.V.R.; investigation, A.G.P.; software, A.G.P.; supervision, S.V.R.; writing—original draft preparation, V.V.K.; writing—review and editing, S.V.R.; visualization, V.V.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Ministry of Science and Higher Education of the Russian Federation (State Assignment No. FSN-2024-0022).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

c	the speed of light
B_z	external magnetic field, T
E_F	Fermi degenerate energy
E_f	energy of the thermonuclear reaction
E	energy, W/kg
H	magnetic induction, T
j_r	current density, A/m ²
k	Boltzmann constant
K	plasma-specific scaling factor
N_{fus}	number of neutrons
n	heavy particle, cm ^{−1}
n_e	electron concentration, cm ^{−1}

P	pressure, Pa
P_e	electron pressure, Pa
P_i	ion pressure, Pa
P_f	fusion power per unit volume, W/m ³
Q_{ei}	energy transferred per unit time per unit volume from electrons to ions
Q_{fus}	local (thermonuclear) energy release to the electron component
q	broadband radiation intensity, W/cm ²
q_L	Laser intensity, W/cm ²
q_r	energy flux from the magnetic field, W/cm ²
q_v	spectral broadband radiation flux, W/cm ²
q_{term}	density of the external broadband radiation flux perpendicular to the target
r	radial coordinate, m
t	time, s
Teq	average plasma temperature
T_e	electron temperature, K
T_i	ion plasma temperature, K
u	velocity along the coordinate, m/s
U_v	spectral flux and volumetric density of broadband radiation
V_D	velocity of the photodetonation wave, m/s
V_f^{nucl}	velocity of the thermonuclear reaction, m/s
$v_{ei,k}$	average frequency of electron–ion collisions, Hz
ρ	density, kg/m ³
λ_e	electron thermal conductivity coefficient, W/(m K)
λ_i	ion thermal conductivity coefficient, W/(m K)
τ	the duration of the broadband radiation pulse, s
φ	the azimuthal angle
Z_1	proton number of the interacting nuclei 1
Z_2	proton number of the interacting nuclei 2
$\bar{Z}_{cp}$	equilibrium average charge of heavy particles
θ	plasma degeneracy parameter
χ	radiative thermal diffusivity coefficient
χ_v	spectral absorption coefficient
γ	adiabatic index of Hugoniot

References

1. Ananyev, S.; Kukushkin, A. Calculation of Consistent Plasma Parameters for DEMO-FNS Using Ionic Transport Equations and Simulation of the Tritium Fuel Cycle. *Appl. Sci.* **2023**, *13*, 8552. [\[CrossRef\]](#)
2. Dlougach, E.; Panasenkov, A.; Kuteev, B.; Serikov, A. Neutral Beam Coupling with Plasma in a Compact Fusion Neutron Source. *Appl. Sci.* **2022**, *12*, 8404. [\[CrossRef\]](#)
3. Garanin, S.G.; Ivanovskii, A.V.; Kulikov, S.M.; Mamyshev, V.I.; Pevny, S.N.; Rogachev, V.G. Inertial Thermonuclear Fusion Using Explosive Magnetic Generators. *Plasma Phys. Rep.* **2022**, *48*, 111–120. [\[CrossRef\]](#)
4. Mitrofanov, K.N.; Aleksandrov, V.V.; Branitski, A.V.; Grabovskiy, E.V.; Gritsuk, A.N.; Oleinik, G.M.; Frolov, I.N.; Olkhovskaya, O.G.; Gasilov, V.A. Progress in researching the implosion of nested arrays of mixed composition and the generation of soft X-ray power pulse. *Plasma Phys. Control Fusion* **2022**, *64*, 045007. [\[CrossRef\]](#)
5. Chetverushkin, B.N.; D’Ascenzo, N.; Saveliev, V.I. Kinetically consistent magnetogasdynamics equations and their use in supercomputer computations. *Dokl. Math.* **2014**, *90*, 495–498. [\[CrossRef\]](#)
6. Zel’Dovich, Y.B.; Rajzer, Y.P. *Physics of Shock Waves and High Temperature Phenomena of Hydrodynamic Phenomena*; Nauka: Moscow, Russia, 1966.
7. Braginskij, S.I. *Transport Processes in a Plasma*; Reviews of Plasma Physics; Leontovich, M.A., Ed.; Consultants Bureau: New York, NY, USA, 1965; pp. 205–311.
8. Samarskij, A.A.; Popov, I.P. *Difference Methods for Solving Problems of Gas Dynamics*; Nauka: Moscow, Russia, 1980. (In Russian)
9. Kuzenov, V.V.; Ryzhkov, S.V.; Varaksin, A.Y. Development of a Method for Solving Elliptic Differential Equations Based on a Nonlinear Compact-Polynomial Scheme. *J. Comput. Appl. Math.* **2024**, *451*, 116098. [\[CrossRef\]](#)

10. Surzhikov, S.T. Computing System for Solving Radiative Gasdynamic Problems of Entry and Re-Entry Space Vehicles. In Proceedings of the 1st International Workshop on Radiation of High Temperature Gases in Atmospheric Entry, ESA-533, Lisbon, Portugal, 8–10 October 2003; pp. 111–118.
11. Kuzenov, V.V.; Ryzhkov, S.V.; Shumaev, V.V. Application of Thomas-Fermi model to evaluation of thermodynamic properties of magnetized plasma. *Probl. At. Sci. Technol.* **2015**, *1*, 97–99.
12. Xu, Z.; Shu, C.-W. Anti-diffusive flux corrections for high order finite difference WENO schemes. *J. Comput. Phys.* **2005**, *205*, 458–485. [\[CrossRef\]](#)
13. Xu, Z.; Shu, C.-W. Anti-diffusive finite difference WENO methods for shallow water with transport of pollutant. *J. Comput. Math.* **2006**, *24*, 239–251.
14. Raizer, Y.P. Breakdown and heating of gases under the influence of a laser beam, *Sov. Phys. Usp.* **1966**, *8*, 650–673. [\[CrossRef\]](#)
15. Kuzenov, V.V.; Ryzhkov, S.V. Small-sized plasma generators—Sources of high-energy particle and neutron fluxes (review). *Fusion Sci. Technol.* **2025**, *81*, 1–11. [\[CrossRef\]](#)
16. Derzhiev, V.I.; Zhidkov, A.G.; Yakovlenko, S.I. *Radiation of Ions in a Nonequilibrium Dense Plasma*; Energoatomizdat: Moscow, Russia, 1986. (In Russian)
17. Paradis, C.; Hammond, D.; Thoma, J.; Loescher, A.; Le Touzé, G.; Friedman, G.; Le Garrec, B.; Chériaux, G. Advances in laser technology for direct drive inertial fusion energy. *Proc. SPIE—Int. Soc. Opt. Eng.* **2025**, *13343*, 1334302. [\[CrossRef\]](#)
18. Follett, R.K.; Colaitis, A.; Seaton, A.G.; Wen, H.; Turnbull, D.; Froula, D.H.; Palastro, J.P. Ray-based cross-beam energy transfer modeling for broadband lasers. *Phys. Plasmas* **2023**, *30*, 042102. [\[CrossRef\]](#)
19. Zhang, X.; Ji, L.L.; Liu, D.; Gao, Y.Q.; Sui, Z.; Zhao, X.H.; Xiang, X. Numerical simulation on third-harmonic generation of super-luminescent light by mixing broadband and narrowband lasers. *Chin. J. Lasers* **2021**, *48*, 2108001. [\[CrossRef\]](#)
20. Zudin, I.; Gushchin, M.; Korobkov, S.; Strikovskiy, A.; Katkov, A.; Kochedykov, V.; Petrova, I. Transformation of the Shape and Spectrum of an Ultrawideband Electromagnetic Pulse in a “Gigantic” Coaxial Line Filled with Magnetized Plasma. *Appl. Sci.* **2024**, *14*, 705. [\[CrossRef\]](#)
21. Nikolenko, A.S.; Gushchin, M.E.; Korobkov, S.V.; Strikovskiy, A.V.; Loskutov, K.N. Dynamics of a Plasma Cloud Generated by a Compact Coaxial Gun upon Expansion into Vacuum and Large-Volume Background Plasma in an External Magnetic Field. *Plasma Phys. Rep.* **2023**, *49*, 1284–1299. [\[CrossRef\]](#)
22. Es’kin, V.A.; Korobkov, S.V.; Gushchin, M.E.; Kudrin, A.V. Propagation of an Ultrawideband Electromagnetic Pulse Along a Plasma-Filled Coaxial Line. *IEEE Trans. Plasma Sci.* **2023**, *51*, 374–380. [\[CrossRef\]](#)
23. Sladkov, A.; Fegan, C.; Yao, W.; Bott, A.F.A.; Chen, S.N.; Ahmed, H.; Filippov, E.D.; Lelièvre, R.; Martin, P.; McIlvenny, A.; et al. Saturation of the compression of two interacting magnetized plasma toroids evidenced in the laboratory. *Nat. Commun.* **2024**, *15*, 10065. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Korobkov, S.V.; Nikolenko, A.S.; Gushchin, M.E.; Strikovskiy, A.V.; Zudin, I.Y.; Aidakina, N.A.; Shaikhislamov, I.F.; Rumenskikh, M.S.; Zemskov, R.S.; Starodubtsev, M.V. Features of Dynamics and Instability of Plasma Jets Expanding into an External Magnetic Field in Laboratory Experiments with Compact Coaxial Plasma Generators on a Large-Scale “Krot” Stand. *Astron. Rep.* **2023**, *67*, 93–103. [\[CrossRef\]](#)
25. Savenko, N.O.; Urvachev, E.M.; Losseva, T.V.; Grushin, A.S.; Poklad, Y.V.; Gasilov, V.A. Numerical Simulation of Plasma Jet Expansion in a Laboratory Experiment. *Plasma Phys. Rep.* **2025**, *51*, 697–707. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.