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# Compression of magnetized target in the magneto-inertial fusion

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**Abstract.** This paper presents a mathematical model, numerical method and results of the computer analysis of the compression process and the energy transfer in the target plasma, used in magneto-inertial fusion. The computer simulation of the compression process of magnetized cylindrical target by high-power laser pulse is presented.

## 1. Introduction

Ongoing experimental and theoretical studies on magneto-inertial confinement fusion (Angara, C-2, CJS-100, General Fusion, MagLIF, MAGPIE, MC-1, YG-1, Omega) and new constructing facilities (Baikal, C-2W, Z300 and Z800) require adequate modeling and description of the physical processes occurring in high-temperature dense plasma in a strong magnetic field [1-7].

Magneto-inertial fusion is an alternative path to the magnetic and inertial fusion, and magnetic field suppresses the thermal conductivity in a magnetized plasma (the target). Thereby, greatly reducing heat losses and increasing the lifetime of the configuration, and hence the thermophysical properties and energy parameters of the system.

This paper presents a detailed description of magneto-plasmodynamic code that allows to perform modeling of X-rays/first wall interaction. This problem is important in assessing the performance of device as the power plant. This mathematical model cannot determine the dynamic response (the evolution of the stress waves and pressures with the strength and compressibility in structural materials) of the first wall on neutron pulse, but the calculations make possible to estimate the interactions between radiation and solid wall, determine the mass of the evaporated material, its temperature, and mechanical impulse.

This work is devoted to the simulation of laser beams interaction with an axisymmetric dense magnetized plasma, e.g., such burning plasma parameters can be produced in magneto-inertial fusion. For this reason the numerical model of the process is based on the multi-component radiation gas dynamics with turbulence model. The radiation transfer is taking into account in multi-group diffusive approach. The main distinguish of this proposed model is the presence of the externally applied magnetic field.

## 2. Mathematical Model

The equation of plasma magnetic field generation is:



$$\frac{\partial \vec{B}}{\partial t} = \text{rot}[\vec{V} \times \vec{B}] - \frac{c^2}{4\pi L_*^2} t_* \text{rot}\left(\frac{\text{rot}\vec{B}}{\sigma}\right), \quad \vec{j} = \sigma \left( \vec{E} + \frac{V_*}{c} [\vec{V} \times \vec{B}] \right),$$

where  $t_*$  is the characteristic exposure time,  $L_*$  is the characteristic size,  $V_*$  is the characteristic velocity,  $\sigma$  is the electrical conductivity coefficient,  $\vec{E}$  is the intensity of electric field,  $\vec{V}$  is the plasma velocity.

Operator *rot* in the cylindrical coordinate system  $(r, z, \varphi)$ :

$$\left(\text{rot}\vec{B}\right)_r = \frac{1}{r} \frac{\partial B_z}{\partial \varphi} - \frac{\partial B_\varphi}{\partial z}, \quad \left(\text{rot}\vec{B}\right)_\varphi = \frac{\partial B_r}{\partial z} - \frac{\partial B_z}{\partial r}, \quad \left(\text{rot}\vec{B}\right)_z = \frac{1}{r} \frac{\partial r B_\varphi}{\partial r} - \frac{\partial B_r}{\partial \varphi}.$$

It is known, that plasma dynamical processes are strongly affected by irradiation, if laser plasma temperature achieves 1 eV. In that case, the gas dynamic fields of thermophysical variables may be calculated only with taking into account the radiation fields. In this work the radiation transfer equation is used in the form of multi-group diffusion approach:

$$\begin{aligned} \frac{1}{J} \frac{\partial (J q_{i\xi})}{\partial \xi} + \frac{1}{J} \frac{\partial (J q_{i\eta})}{\partial \eta} + \chi_i c U_i &= 4 \chi_i \sigma_i T^4, \\ \frac{c}{3} \frac{\partial U_i}{\partial \xi} + \chi_i q_{i\xi} &= 0, \quad \frac{c}{3} \frac{\partial U_i}{\partial \eta} + \chi_i q_{i\eta} = 0, \end{aligned}$$

where  $U_i(y, z, t)$  is the radiation power density in  $i$ -th spectral group,  $\chi_i$  is the spectral absorption coefficient. Besides of the method mentioned above, the discrete ordinates method has been used in the work, which gets an opportunity to solve the radiation transfer equation on tetrahedral non-structured mesh. Modified alternatively triangular three-layered iterative scheme is applied for the solution of radiation transport equations, where the time step is selected via the conjugate directions method.

One can use the mechanism of continuum absorption, the opposite to electron bremsstrahlung process under conditions of local thermodynamic equilibrium, to define the plasma absorption coefficient for laser radiation:

$$\chi_\omega = \frac{4,97 g Z_i n_i n_e}{n_c^2 \lambda^2 (kT_e)^{3/2}} \frac{1}{\sqrt{1 - n_e/n_c}},$$

where  $\lambda$  is the laser radiation wavelength ( $\mu\text{m}$ ),  $n_e, n_i$  are the electron and ion densities correspondingly ( $\text{cm}^{-3}$ ),  $kT_e$  is the electron temperature (keV),  $g$  is the Gaunt factor,  $n_c = 10^{21} \times \lambda^{-2}$  is the critical electron density ( $\text{cm}^{-3}$ ).

The turbulent viscous coefficient  $\mu_\Sigma^{\perp, \parallel}$  is calculated by using of the Boussinesq hypothesis, when the effective viscous coefficient is  $\mu_\Sigma^{\perp, \parallel} = \mu_m^{\perp, \parallel} + \mu_t$ , where  $\mu_m^{\perp, \parallel}$  is a molecular viscosity coefficient and  $\mu_t$  is a turbulent one, determined from  $q-\omega$  turbulence model. The equations of  $q-\omega$  turbulence model in curvilinear coordinates  $\xi, \eta$  are:

$$\frac{\partial \rho q}{\partial t} + \frac{d\xi}{dt} \frac{\partial \rho q}{\partial \xi} + \frac{d\eta}{dt} \frac{\partial \rho q}{\partial \eta} + \frac{1}{J} \frac{\partial (J \rho V_{\xi} q)}{\partial \xi} + \frac{1}{J} \frac{\partial (J \rho V_{\eta} q)}{\partial \eta} + \alpha \frac{\rho q u}{r} = S_q + \frac{\rho q}{2\omega} \left( C_{\mu} f D - \frac{2}{3} \omega \operatorname{div} \vec{V} - \omega^2 \right),$$

$$\frac{\partial \rho \omega}{\partial t} + \frac{d\xi}{dt} \frac{\partial \rho \omega}{\partial \xi} + \frac{d\eta}{dt} \frac{\partial \rho \omega}{\partial \eta} + \frac{1}{J} \frac{\partial (J \rho V_{\xi} \omega)}{\partial \xi} + \frac{1}{J} \frac{\partial (J \rho V_{\eta} \omega)}{\partial \eta} + \alpha \frac{\rho \omega u}{r} = S_{\omega} + \rho \left( C_1 \left( C_{\mu} D - \frac{2}{3} \omega \operatorname{div} \vec{V} \right) - C_2 \omega^2 \right),$$

$$S_q = \frac{1}{J} \frac{\partial \left\{ J \left( \mu_{\Sigma q}^{\perp} \xi_r^2 + \mu_{\Sigma q}^{\parallel} \xi_z^2 \right) q_{\xi} + \frac{J \left( \mu_{\Sigma q}^{\perp} \xi_r \eta_r + \mu_{\Sigma q}^{\parallel} \xi_z \eta_z \right) q_{\eta}}{\partial \xi} \right\}}{\partial \xi} + \frac{1}{J} \frac{\partial \left\{ J \left( \mu_{\Sigma q}^{\perp} \eta_r \xi_r + \mu_{\Sigma q}^{\parallel} \eta_z \xi_z \right) q_{\xi} + J \left( \mu_{\Sigma q}^{\perp} \eta_r^2 + \mu_{\Sigma q}^{\parallel} \eta_z^2 \right) q_{\eta} \right\}}{\partial \eta} + \alpha \frac{\mu_{\Sigma q}^{\perp}}{r} \left\{ \xi_r \frac{\partial q}{\partial \xi} + \eta_r \frac{\partial q}{\partial \eta} \right\},$$

$$S_{\omega} = \frac{1}{J} \frac{\partial \left\{ J \left( \mu_{\Sigma \omega}^{\perp} \xi_r^2 + \mu_{\Sigma \omega}^{\parallel} \xi_z^2 \right) \omega_{\xi} + \frac{J \left( \mu_{\Sigma \omega}^{\perp} \xi_r \eta_r + \mu_{\Sigma \omega}^{\parallel} \xi_z \eta_z \right) \omega_{\eta}}{\partial \xi} \right\}}{\partial \xi} + \frac{1}{J} \frac{\partial \left\{ J \left( \mu_{\Sigma \omega}^{\perp} \eta_r \xi_r + \mu_{\Sigma \omega}^{\parallel} \eta_z \xi_z \right) \omega_{\xi} + J \left( \mu_{\Sigma \omega}^{\perp} \eta_r^2 + \mu_{\Sigma \omega}^{\parallel} \eta_z^2 \right) \omega_{\eta} \right\}}{\partial \eta} + \alpha \frac{\mu_{\Sigma \omega}^{\perp}}{r} \left\{ \xi_r \frac{\partial \omega}{\partial \xi} + \eta_r \frac{\partial \omega}{\partial \eta} \right\},$$

$$\mu_{\Sigma q}^{\perp \parallel} = \mu_m^{\perp \parallel} + \mu_t, \quad \mu_{\Sigma \omega}^{\perp \parallel} = \mu_m^{\perp \parallel} + 1,3 \mu_t, \quad \mu_t = C_{\mu} f(n) \rho \frac{q^2}{\omega},$$

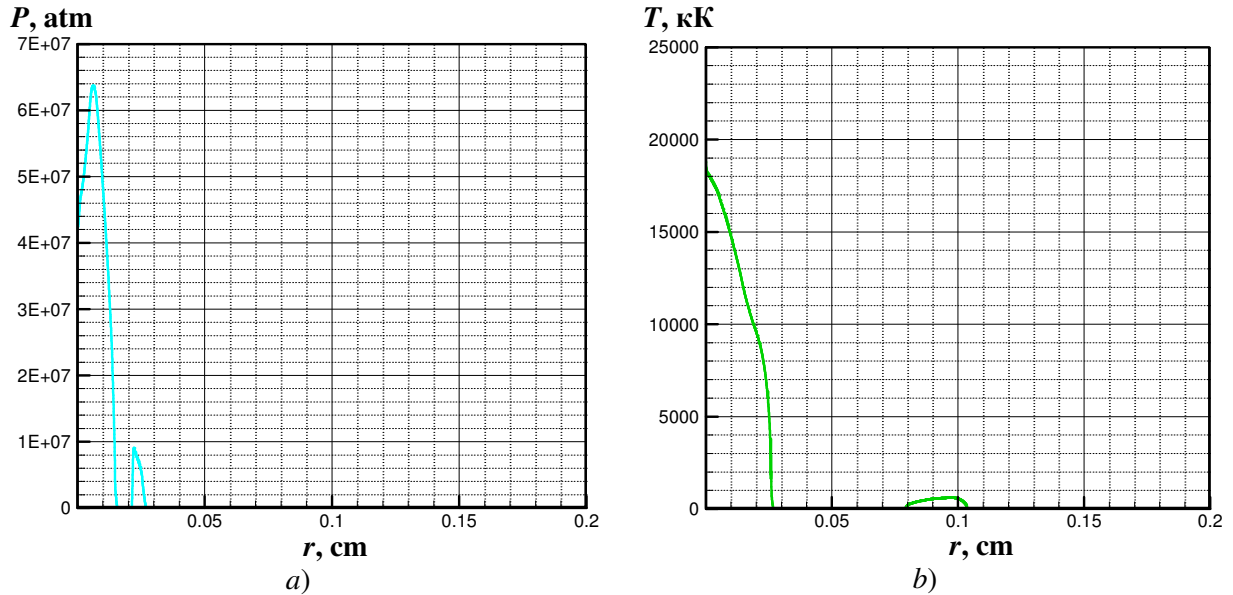
$$C_1 = 0,045 + 0,405 f(n), \quad C_2 = 0,92, \quad C_{\mu} = 0,09, \quad f(n) = 1 - \exp \left( -0,0065 \frac{\rho q n}{\mu_m^{\perp \parallel}} \right),$$

where  $q$  is a pseudo velocity and  $\omega$  is a pseudo vortex,  $f(n)$  is a wall function for correct flux parameters evaluation in laminar sub-layer near a solid streamline surface,  $n$  is the distance by normal from the given point to the nearest surface.

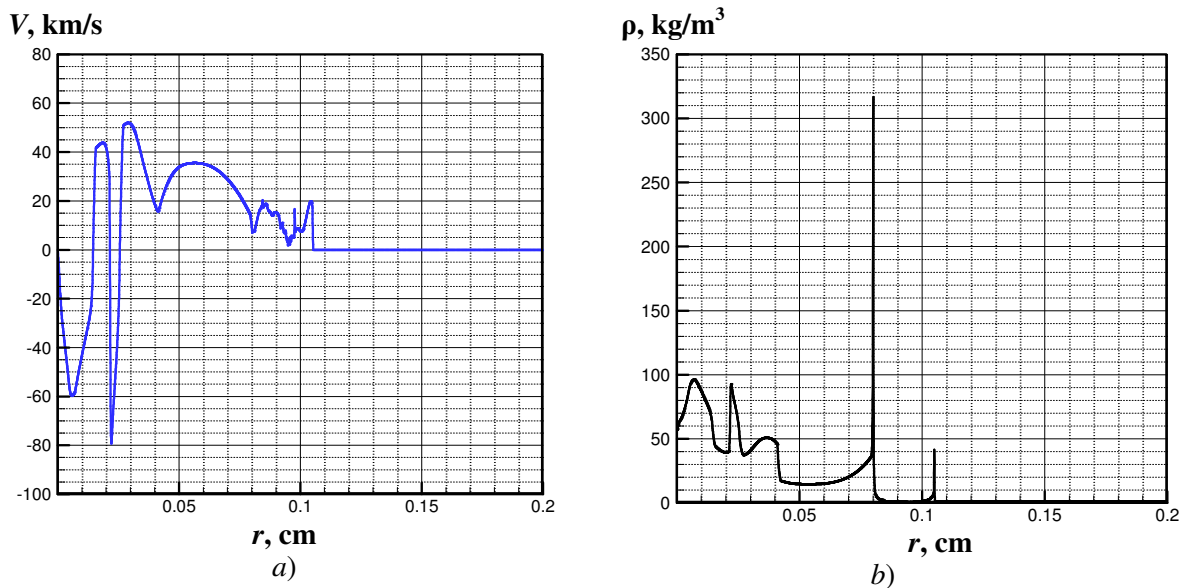
### 3. Results

Initial values of the intensity of the seed magnetic field in the rarefied medium reach the fraction of  $T$ . Results of computational modeling [8-10] are presented below. Calculations carried out for the Nd laser radiation for forming rectangular shape (impulse duration = 10 ns). The laser radiation flux is  $q_{las} = 2 \cdot 10^{14}$  W/cm<sup>2</sup>. A thin metallic cylindrical shell material is Al. The target radius is 0.1 cm.

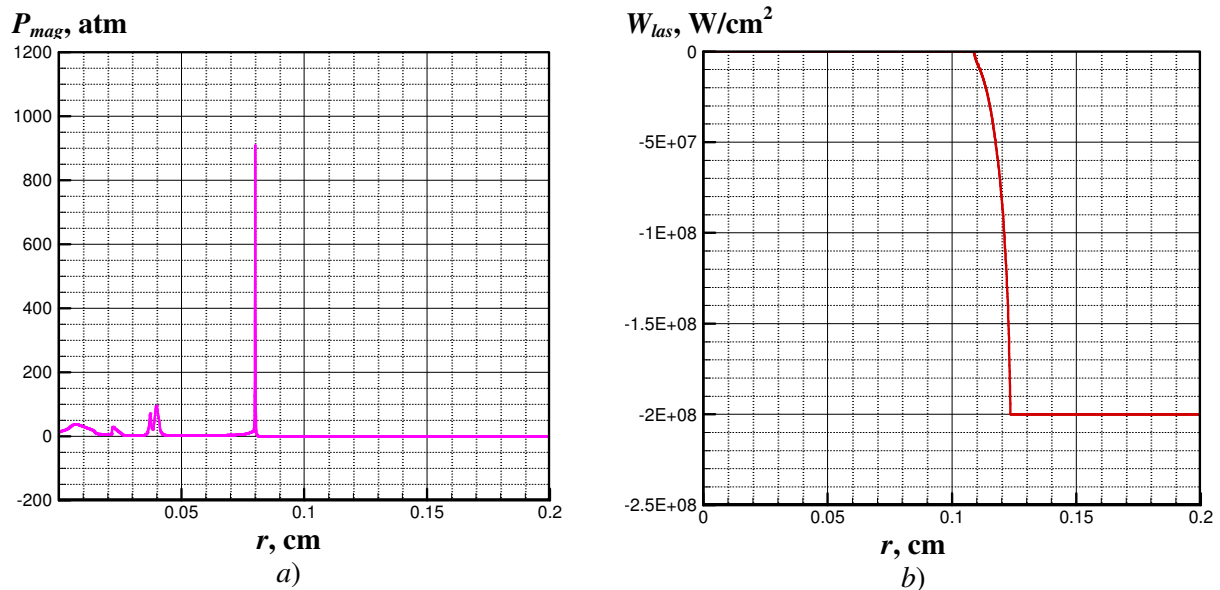
Theoretical results for the case of double-layer target for laser-driven magneto-inertial fusion are presented below. Spatial distribution of the pressure  $P$  and temperature  $T$ , velocity  $V$  and density  $\rho$  of the plasma at time 5.66 ns (the pulse duration is 10 ns) is shown in figures 1-2. The distributions of the magnetic pressure  $P_{mag}$  and laser radiation  $W_{las}$  along the radial coordinate are shown in figure 3. These distributions correspond to the "expansion" stage of plasma formation ( $t = 5.66$  ns).



**Figure 1.** Spatial distribution of the plasma pressure (a) and temperature (b) at time  $t = 5.66$  ns. The laser pulse duration  $t_{Las} = 10$  ns and the laser radiation flux  $q_{las} = 2 \cdot 10^{14}$  W/cm<sup>2</sup>.



**Figure 2.** Plasma velocity (a) and density (b) at  $t = 5.66$  ns as a function of radial coordinate.



**Figure 3.** Distribution of the magnetic pressure (a) and laser radiation (b) at  $t = 5.66$  ns ( $t_{Las} = 10$  ns).

#### 4. Conclusion

The non-stationary two dimensional radiation magneto-gas dynamic model is developed. The mathematical model takes into consideration the magnetized plasma compressed by laser beams of high energy pulses and high speed plasma jets. It is based on radiation plasma dynamics equations in arbitrary curvilinear coordinates. An improved two-dimensional radiation-hydrodynamics code which simulates plasmas in cylindrical or spherical geometries is designed. It solves single-fluid, two-temperature equations of motion with contributions from diffusion, convection, heat conduction. Electromagnetic processes are described by the Maxwell-Ohm equations in plasma with final conductivity. The transport coefficients in the given system of the equations taking into account magnetized laser plasma. The model is based on splitting method in terms of physical processes and spatial directions, that in spatially smooth solution allows to get seventh order of accuracy.

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