The choice of the energy embedding law in the design of heavy ionic fusion cylindrical targets

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Abstract. The paper considers the numerical design of heavy ion fusion (FIHIF) targets, which is one of the branches of controlled thermonuclear fusion (CTF). One of the important tasks in the targets design for controlled thermonuclear fusion is the energy embedding selection whereby it is possible to obtain "burning" (the presence of thermonuclear reactions) of the working DT region. The work is devoted to the rapid ignition of FIHIF targets by means of an additional short-term energy contribution to the DT substance already compressed by massively more longer by energy embedding. This problem has been fairly well studied for laser targets, but this problem is new for heavy ion fusion targets. Maximum momentum increasing is very technically difficult and expensive on modern FIHIF installations. The work shows that the additional energy embedding ("igniting" impulse) reduces the requirements to the maximum impulse. The purpose of this work is to research the ignition impulse effect on the FIHIF target parameters.

1. Introduction

A microtarget is a layered system wherein one layer, called a "working" layer, consists of a deuterium-tritium blend (DT) or another blend wherein thermonuclear reactions occur. The target is either irradiated from the outside, or the energy is embedded in the inner layer. Under the action of this energy, the "working" region is compressed and "burning" begins. So thermonuclear reactions occur, as a result of which energy is released.

The main microtargets design tasks for controlled thermonuclear fusion (CTF) are a selection of the geometry (size and composition of layers) and the law of energy embedding wherein it is possible to obtain "burning" (the presence of thermonuclear reactions) of the working DT region. At the same time, the energy output as a result of thermonuclear reactions should be greater than the embedded energy (the thermonuclear gain coefficient is greater than one). And an important question is the amount of energy that is being embedded.

The work is devoted to the rapid ignition of FIHIF targets by means of an additional short-term embedding of energy to the DT substance already compressed by massively more longer by energy embedding. This problem has been fairly well studied for laser targets [1,2], but this problem is new for heavy ion fusion targets.

The maximum impulse increase is very difficult technically and expensively on modern FIHIF installations. The paper shows that additional energy embedding ("igniting" impulse) reduces the requirements to the maximum impulse (driver). The purpose of this work is to research the ignition impulse effect on the FIHIF target parameters.
2. Research objective
There is considered the cylindrical layered system (target) of the form:

![Figure 1. Appearance of the target](image)

The target is an axisymmetric cylindrical structure (of a certain length) consisting of nested layers made of different substances.

Functionality of the system layers:
- a central layer (rod) of DT is energy source in the implementation of thermonuclear fusion reactions;
- a shell of a heavy substance (Au) is a pusher which compresses the DT layer during energy cumulation and at the same time is a shield for thermal insulation of DT fuel from a heated energy embedding region;
- the energy embedding region is intended for high-speed heavy ion beams deceleration and accumulating energy from an external source;
- an outer heavy shell (Au) is designed to reduce the radial expansion of the layers outward, which increases the amount of cumulative energy.

The target ends remain free. Through them heavy ion fluxes of high energy are injected left and right into the light layer (Be) from an external source. The energy embedding mechanism is realized by means of focused beams directed parallel to the system axis. To realize axial symmetry of motion, the beams rotate in circular orbits with a high frequency. The ion flux deceleration is carried out in the light layer almost evenly along the length. Such energy embedding keeps the motion axisymmetric.

The ions deceleration in the target layers matter causes intense heating and subsequent expansion. In this case, the motion in the axis direction leads to the energy cumulation in its vicinity. Expansion from the open ends, as calculations in the complete (two-dimensional) formulation [3] show, cover only limited parts of the target, while retaining its large part unaffected. Therefore, in a significant part of the target, outside the vicinity of the ends, the motion remains only radial (one-dimensional). The movement in this part of the target is studied, i.e. there is one-dimensional target of the form:

![Figure 2. Geometry of the target section perpendicular to its axis.](image)

A unshocked compression idea of the working DT region is used when designing targets.
What does unshocked compression give?

Large compressions and large densities can be obtained even endless if one has sufficient energy to compress.

To reproduce unshocked compression at the right boundary of the working (DT) region, the velocity and pressure in the case of an ideal gas must be respectively equal (these dependences were obtained by Stanyukovich K.P. [4]):

\[ u_l = \frac{2}{\gamma - 1} c_0 \left[ 1 - \left( 1 - \frac{c_0}{L_0} t \right)^{\frac{2\gamma}{\gamma + 1}} \right] \]  \hspace{1cm} (1)

\[ P_l = \frac{P_0}{\gamma} \left( 1 - \frac{c_0}{L_0} t \right)^{\frac{2\gamma}{\gamma + 1}} = P_0 \left( 1 - \frac{c_0}{L_0} t \right)^{\frac{2\gamma}{\gamma + 1}} \]  \hspace{1cm} (2)

where \( L_0 \) - length of compressible layer, \( \rho_0, c_0 \) - respectively initial density and sound velocity, \( \gamma \) - adiabatic index, \( t \) - current time.

Within the framework of the shell system (Figure 2.), the energy embedding law \( Q(t) (dE_2 / dt = Q(t)) \) in the region of mass \( m_2 \) can be selected such that on the right boundary of the region with mass \( m_0 \) we the velocity and pressure values \( u_l(t), P_l(t) \), necessary for carrying out the unshocked compression of this region, i.e. blend of DT gas with mass \( m_0 \) [7], are obtained.

\[ Q(t) = 2\gamma c_0^3 G L_0^a / \left( (\gamma - 1)^2 m_2 \right). \]

\[ \left\{ \begin{array}{l}
- (1 - \xi^{-(\gamma - 1)(\gamma + 1)})^2 + \left[ \frac{V_2(0)}{aL_0^\alpha} + (\gamma - 1) + 2\xi - (\gamma + 1)\xi^{2\gamma/(\gamma + 1)} \right] \\
\frac{\xi^{2\gamma/(\gamma + 1)} L_0^{\alpha - 1}}{\gamma + 1}
\end{array} \right. \]

\[ \xi = 1 - c_0 t / L_0 \ (0 \leq \xi \leq 1), \ G = m_0(1 - 2k_2) / \gamma + 2k_1 / (\gamma + 1) + (\gamma + 1)m_0^2 k_3 / \gamma^2, \]

\[ a = \left( \left( m_1 + m_2 + m_3 + (\gamma + 1)\rho_0 L_0^\alpha / (2\gamma) \right) / (\gamma - 1)(m_2 / 2 + m_3) \right) / (m_3 + m_2 / 2)^2, \]

\[ k_1 = m_1 + m_2 + m_3 + (\gamma + 1)\rho_0 L_0^\alpha / (2\gamma) \]

\[ k_3 = 3(m_3 + m_2 / 3) / (2(m_3 + m_2 / 2)^2). \]

where \( m_l \) - layers mass, \( \alpha \) - parameter that depends on the geometry type.

Figure 3 shows the function type \( Q(t) \) is for a specific target with \( c_0 = 0.01 \) and \( L_0 = 0.1 \) (the length is measured in cm, the time is 10-7 seconds, the power \( Q(t) \) is 0.01 TW/g).
Figure 3. Function type $Q(t)$.

$Q(t)$ quantitatively differs in different calculations depending on the geometry ($m_i$), the maximum value of $Q^*$, the values of $c_0$ and $L_0$, but the curves form is the same (with peaking).

It stands to mention a number of the moments arising in the unshocked compression.

Firstly, with unshocked compression, it is possible to obtain high parameters of the compressible gas (DT gas density).

Secondly, the main shortcoming in the immediate implementation of unshocked compression is the need for unlimited energy embedding growth and it can be eliminated. This is achieved by the kinetic energy accumulation in the heavy shell with the mass $m_1$ in the energy embedding course. The energy embedding termination is offset by the subsequent release of the stored kinetic energy gas in the region $m_1$ (Figure 2).

Thirdly, under classical unshocked (cold) compression in the fuel for burning, the temperature of its heating is not sufficient, although the "ignition" criterion $\rho R \sim \int_{DT} \rho dr$ is fulfilled with a large margin due to high densities under the unshocked compression. The final temperature can be raised by increasing the initial heating (by increasing the parameter $c_0$), as well as by breaking the unshocked compression mode at its final stage.

During microtargets development, it is also necessary to take into account the design characteristics of the installation where experiments with this target are planned. The proposed "plan" of energy embedding in the shell microtarget design, the variant of which is shown in Fig. 2, will be described.

According to the found law $Q(t)$ the energy embedding is determined by the time $t^*$ $(0 \leq t \leq t^*)$, wherein the aggravation of the impulse $Q(t)$ reaches the maximum value for setting $Q^* = Q(t^*)$. Then the energy embedding occurs up at a constant $Q^*$ to the time $t^{**}$. The moment $t^{**}$ is determined by the achievement of an average region density with a mass $m_0$ of a value that would exceed the ignition criterion $\rho R$. However, the set values $\rho R$ for unshocked compression do not yet ensure the ignition of the DT gas blend. Its temperature is insufficient. Then it can be do two things. Firstly, it can be to invest energy with the maximum exacerbation magnitude into the region with the mass $m_2$ up to a certain value, until the target ignites (one-impulse energy embedding). And secondly, it is possible to make additional energy embedding in the form of a impulse with intensity $F_{DT}$ ("igniting" impulse) at the moment $t^{**}$ when the necessary density criterion for ignition in the DT gas region is reached. Due to this, it is possible to effect active burning of DT gas in the DT region (two-impulse energy embedding).
The one impulse regime of compression and burning of FIHIF targets is similarly described in [6, 7].

3. Calculations results
Figure 4 shows a computational comparison of the two-impulse and one-impulse compression and burning scenarios is given in the example of the cylindrical target. Calculations were made using models that adequately describe the plasma physics [8].

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{DT} & \text{Au} & \text{Be} & \text{Au} \\
\hline
r & 0 & 0.1 & 0.105 & 0.195 & 0.222 \text{ (cm)} \\
\rho & 0.05 & 19.3 & 1.8 & 19.3 \text{ (g/cm}^3\text{)} \\
\hline
\end{array}
\]

**Figure 4.** Specific type of target.

The motion of the system in the two-temperature approximation, the energy transfer by electrons and ions, the kinetics of thermonuclear reactions, the spectral energy transfer by photons and their interaction with matter are calculated. The external energy embedding \(Q(t)\) is given in the region Be. Figure 3 shows the form of the function \(Q(t)\).

The system of units wherein the results are given: the time in 110-7 sec, the length in cm, the energy in 0.1 MJ.

There is introduced the following notation:
- \(t^*\) - an instant of time before which the energy embedding is carried out according to the scheme of unshocked compression;
- \(Q^*=Q(t^*)\) – maximum exacerbation of energy embedding;
- \(F(t^*)\) – full energy embedding (according to the scheme of unshocked compression);
- \(t^{**}\) - a moment of the external energy embedding end and a moment of the second impulse of the direct embedding in DT;
- \(F(t^{**})\) – energy embedding in the time interval \(0<t<t^{**}\);
- \(F_{DT}\) – an instantaneous energy embedding in the region DT at two-impulse energy;
- \(F_{emb}\) – energy, nested in the target for two impulses;
- \(F_{ign}\) – a value released in the DT thermonuclear energy;
- \(K\) - coefficient of thermonuclear gain (ratio \(F_{ign}/F_{emb}\)).

The table 1 shows the results of target calculations for two-impulse and single-impulse energy embedding.
Table 1. Results of target calculations

| №  | I            | II           | III           | IV            |
|----|--------------|--------------|---------------|---------------|
| t* | 9.9786       | 9.9786       | 9.96476       | 9.96994       |
| F(t*)| 0.02625 | 0.02625 | 0.0246 | 0.0309 |
| Q* | 30           | 30           | 50            | 75            |
| t**| 10.2126      | 10.2126      | 10.25         | 10.157        |
| F(t**) | 0.38384 | 0.38384 | 0.2679 | 0.3895 |
| F_{DT} | 0         | 0.03        | 0             | 0             |
| F_{emb} | 0.38384 | 0.4138     | 0.2679        | 0.3895        |
| F_{ign} | 0.0002  | 15.72       | 0.996         | 3.417         |
| K   | 0.0012       | 21.4         | 3.72          | 8.77          |

The first column is the result of calculating $Q^* = 3$, without additional energy embedding in the DT layer. In this case, about 0.38 energy units are invested in the target and it does not light up ($F_{ign} = 0.0002$). The second column shows the result of calculations for additional energy embedding in the DT gas region (two-impulse energy embedding). The second impulse is $F_{DT} = 0.03$, i.e. about 1% of the energy is invested from the nested one at the first impulse. The additional impulse value is chosen to equalize the energy embedding values for the single-impulse and two-impulse energy embedding, although calculations show that the target can be ignited at a lower energy of the second impulse.

The third and fourth columns are the calculations results with the single-impulse energy embedding, but an increased value of $Q^*$.

The third column is the result of calculation with $Q^* = 50$, and the fourth is the results of calculations with $Q^* = 75$.

The approach wherein the ignition is carried out by means of the additional energy directly into the DT fuel by the second impulse, is attractive. It is possible to ignite the target with a smaller exacerbation amount, and the energy output for an equally enclosed energy is 5.8 times larger (look at columns 2 and 4).

4. Conclusion

The ignition impulse performs the same role as increase of the main energy embedding power aggravation from $Q^* = 30$ to $Q^* = 75$.

The igniting impulse presence activates the "burning" of the target. With the same embedded energy, the thermonuclear gain coefficient increases by 5.5 times.

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