AIP Conference Proceedings

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Citation: AIP Conference Proceedings **1698**, 040011 (2016); doi: 10.1063/1.4937847
View online: http://dx.doi.org/10.1063/1.4937847
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1698?ver=pdfcov
Published by the AIP Publishing

The Comparison of Extraction of Energy in Two-cascade and One-cascade Targets

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Abstract. The paper is devoted to numerical designing of cylindrical microtargets on the basis of shock-free compression. When designing microtargets for the controlled thermonuclear fusion, the core tasks are to select geometry and make-up of layers, and the law of energy embedding as well, which allow receiving of "burning" of deuterium-tritium mix, that is, the existence of thermonuclear reactions of working area. Yet, the energy yield as a result of thermonuclear reactions has to be more than the embedded energy (the coefficient of amplification is more than a unit). So, an important issue is the value of the embedded energy. The purpose of the present paper is to study the extraction of energy by working DT area in one-cascade and two-cascade targets. A bigger extraction of energy will contribute to a better burning of DT mix and a bigger energy yield as a result of thermonuclear reactions. The comparison of analytical results to numerical calculations is carried out. The received results show advantages of a two-cascade target compared to a one-cascade one.

INTRODUCTION

A microtarget is a layered system in which one layer called "working" consists of deuterium-tritium mix (DT) or other mix in which thermonuclear reactions occur. The target is irradiated outside, or energy is embedded in an inside layer. Under the action of this energy, the "working" area compresses and the "burning" begins, i.e. thermonuclear reactions occur resulting in energy emission.

When designing microtargets for the controlled thermonuclear fusion, the core tasks [1-4] are to select geometry (the size and make-up of layers) and the law of energy embedding, which allow receiving of burning of working area. Yet, the energy yield as a result of thermonuclear reactions has to be more than the embedded energy (the coefficient of amplification is more than a unit). So, an important issue is the value of the embedded energy.

An elementary idea of a thermonuclear target of direct energy embedding is given by the spherical or cylindrical layered system presented in Fig. 1.

$\downarrow Q_2$

|----------|-----------|//////////////|-----------|

m_0 m_1 m_2 m_3

FIGURE 1. Geometry of a one-cascade target

Advanced Materials in Technology and Construction (AMTC-2015)
AIP Conf. Proc. 1698, 040011-1–040011-6; doi: 10.1063/1.4937847

The m_0 area is a thermonuclear fuel, working DT area. The areas m_1, m_3 are thin layers of heavy substances which constrain scattering of the DT area and all system, respectively; energy embedding is performed into the m_2 area by law Q_2(t). Such targets are called one-cascade.

The complication of the design of a layered target can be carried out through increasing the number of layers, moreover, the energy embedding will already be in two layers: in the second Q_2(t) and in the fourth Q_4(t). Such targets are called two-cascade (Fig. 2).

$$\begin{array}{cccccc} & & \downarrow Q_2 & & \downarrow Q_4 & \\ |\text{----------}| & \text{---------}| & /////////// | & \text{-----------}| & ///////// | & \text{----------}| \\ m_0 & m_1 & m_2 & m_3 & m_4 & m_5 \end{array}$$

FIGURE 2. Geometry of a two-cascade target

The purpose of the present paper is to study the extraction of energy by working DT area in one-cascade and two-cascade targets. A bigger extraction of energy will contribute to a better burning of DT mix and a bigger energy yield as a result of thermonuclear reactions.

ENERGY CUMULATION IN ONE-CASCADE SYSTEM

Consider a one-cascade system (Fig. 1). As shown in [5], the value of the extraction of energy by working DT area is equal to:

$$E_{ot} = \left\{ \left(E_2(0) + \frac{Q_2(t)t}{2} \right) m_2^L \left[1 - \left(\frac{V_2^L(0)}{V_2^L(t)} \right)^{\gamma-1} \right] - \frac{\sigma_0 \left(\rho_0^0\right)^{\gamma-1}}{\gamma-1} \left(\frac{V_0(0)}{V_0(t)} \right)^{\gamma-1} m_0 \right\} \Big/ \left(1 + \frac{m_2^L}{m_1} \right). \tag{1}$$

Here $\sigma_0 = \dfrac{(\gamma-1)^{\gamma} u_1^2 (r_1)}{2(\gamma+1)^{\gamma-1} \left(\rho_0^0\right)^{\gamma-1}}$,

ρ_0^0 – the initial density of a layer having mass m_0,

γ – the adiabatic exponent,

$E_2(0)$ – the energy in layer 2 at the initial time point,

$V_2(0)$ – the volume of *i*- area,

V_2^L(t) – the volume of m_2 area to the line of zero speed, its mass

$m_2^L = \dfrac{m_2 (m_3 + m_2 / 2)}{m_1 + m_2 + m_3}$,

$\beta = \dfrac{2\alpha^2}{(\alpha+1)(2\alpha+1)}$,

where α – the parameter depending on the type of geometry:

$\alpha = 1$ – for flat geometry;
$\alpha = 2/3$ – for cylindrical geometry;
$\alpha = 0.5$ – for spherical geometry [1].
The lower indexes of values designate the number of a layer.

A characteristic feature of compression, assuming $u_1(0) = u_3(0) = 0$, and taking into account the possibility of representation of speed in the area of energy embedding (layer m_2) as linear dependence on m: $u(m,t) = \frac{1}{m_2}\left[u_1(t)(m_2 - m) + u_3(t)m\right]$, is the existence of the line of zero speed in layer 2, that is, there exists a particle with mass m_2^L, which moves with a zero speed $u\left(m_2^L, t\right) = 0$. It divides layer 2 into two parts: the left with mass – m_2^L and the right with mass – $m_2^P = m_2 - m_2^L$.

Its Lagrangian coordinate is, first, time invariant, and, secondly, it does not depend on initial energy $E_2(0)$ and energy embedding $Q_2(t)$. Due to existence of the line of zero speed, the energy that is embedded in the area m_2^P, practically does not work for compression of the working DT area, but is used only for scattering of an external layer.

ENERGY CUMULATION IN TWO-CASCADE SYSTEM

In a two-cascade system (Fig. 2), the energy embedding occurs in two layers already (the second and the forth). As shown in [5], the energy extracted by working area (with mass m_0) is equal:

$$E_{ot} = \left(m_3 + \frac{m_2 + m_4^{л}}{3} - \frac{m_2(1-N)\left(m_3 + \frac{m_2 + m_4^{л}}{3}\right)}{3\left(m_1 + m_2/2\right)}\right)\frac{3M}{JNm_2} - \frac{u_3 m_2(1-N)M}{N\left(m_1 + m_2/2\right)} + \tag{2}$$

$$\frac{3M}{JNm_2}\left\{u_5^2\left(m_5 + \frac{m_4^L}{3}\right) - 2\left(E_2(t_1) + \frac{Q_2(t)}{2}\right)m_2\left[1 - \left(\frac{V_2(0)}{V_2(t)}\right)^{\gamma-1}\right] - 2E_4(0)m_4\right\}$$

Here

$$N = \frac{3\left(m_3 + \frac{m_2 + m_4^L}{2}\right)\left(m_1 + \frac{m_2}{3}\right)}{m_2\left(m_1 + \frac{m_2}{2}\right)},$$

$$M = m_3 + \frac{m_2 + m_4^L}{2},$$

$$u_3 = -\frac{u_1\left(m_1 + m_2/2\right) + J}{m_3 + \frac{m_2 + m_4^L}{2}},$$

$$J^2(\mathrm{t}_1) = \frac{2m_4\left[E_4(0) + \frac{Q_4 t_1}{2}\right]\left[1 - \left(\frac{V_4(0)}{V_4(t_1)}\right)^{(\gamma-1)}\right]}{\frac{m_3 + \frac{m_4^L}{3}}{\left(m_3 + \frac{m_4^L}{2}\right)^2} + \frac{m_5 + \frac{m_4^P}{3}}{\left(m_5 + \frac{m_4^P}{2}\right)^2}}.$$

$m_4^L = \frac{m_4\left(m_5 + m_4/2\right)}{m_3 + m_4 + m_5}$ - the mass of the m_4 area to the point of zero speed,

t_1 - the moment of beginning of energy embedding into the external cascade.

In a two-cascade target, besides the line of zero speed in the external cascade (the area with the mass m_4), the layer 2 has a Lagrangian particle of the mass:

$$m_2^* = m_2 \frac{m_3 + \dfrac{m_2 + m_4^L}{2}}{m_1 + m_2 + m_3 + m_4^L/2},$$

which moves with the constant speed $u^* = -\dfrac{J(t_1)}{M}$.

The speed u^* and Lagrangian coordinate of this particle does not depend on the initial energy $E_2(0)$ and energy embedding $Q_2(t)$.

ANALYTICAL AND NUMERICAL COMPARISON OF EXTRACTION OF ENERGY IN TWO CASCADES

The comparison of analytical results to numerical calculations is carried out in the beginning on a model flat task as the formulae (1), (2) given above are received for a flat case. The geometry of a model two-cascade system is given in Fig. 3.

```
I------I---------¦\\\\\\\\¦-----------------¦\\\\\\\\¦---------------I
r: 0      7.9      8.23      10.45            11.33     13.25           13.4
ρ:  0.0001     18.5      1.85            18.5          1.85         18.5
```

FIGURE 3. Geometry of a model two-cascade system

If the fourth and fifth layers are not considered, we have a one-cascade system.

At the initial time point, in the inside layer 2, the initial energy $E_2(0) = 0.243$ is set in one-cascade system ($E(0) = E_2(0)m_2 = 1$) and $E_2(0) = 0.1215$ in two-cascade system. In the two-cascade system, the energy is also set immediately (at the initial time point) in the fourth area having mass m_4 $E_4(0) = 0.14$. Total energy in the two-cascade system is $E(0) = E_2(0)m_2 + E_4(0)m_4 = 1$. That is, the energy embedded in both targets is equal. We simplify the task and suppose $Q_2(t) = Q_4(t) = 0$.

The system of units for the results presented in Table 1 is not given as only relative values for two targets are considered. The energy embedded in both targets is identical.

TABLE 1. Results of comparison at a time point $t = 1$ for two calculations

	One-cascade target		**Two-cascade target**	
	E_{ot}	u_1	E_{ot}	u_1
calculations	0.025	0.1015	0.248	0.35
formulae	0.0211	0.102	0.222	0.33

The figures in the last line are received analytically on the formulae (1), (2) given above, in the third line they are received numerically. As seen from the table, numerical and analytical results are quite consistent. The extraction of energy (at equally embedded energy) is much more in the two-cascade system. It means that there will be more compression and higher temperature of a DT layer, its more intensive burning and bigger thermonuclear energy yield in the working area at one and the same embedded energy.

The second calculation is a real cylindrical target in which the working area is compressed in a shock-free way [6-9]. Calculations are performed on the model which appropriately describes difficult physics of plasma.

We will list some physical processes which need to be considered for the appropriate description of physics of laser plasma:

- absorption and transfer of high-intensity laser radiation in plasma;
- motion of plasma in two-temperature approach with regard to physical viscosity;
- transfer of non-equilibrium radiation and its interaction with substance;
- transfer and exchange of energy by electrons and ions;
- ionization of substance and excitation of ions in non-equilibrium non-stationary plasma;
- kinetics of thermonuclear and neutron and nuclear reactions;
- transfer of neutrons;
- turbulent mixing;
- transfer of energy, impulse and mass by fast charged particles, by both products of thermonuclear and neutron and nuclear reactions, and recoil nuclei.

The system of units under consideration: length – cm, time – 10^{-7} s, mass – g, temperature – keV, energy – 10^{-1} mJ.

The layers 1, 3, 5 consist of dense materials (“heavy” layers), energy is introduced into “light” layers 2, 4.

m_0 m_1 m_2 m_3

|-----------|---------------|////////////////|----------------|

r: 0 0.2 0.21 0.32 0.345

ρ: 0.05 20 6 20

FIGURE 4. Geometry of a one-cascade target

m_0 m_1 m_2 m_3 m_4 m_5

|--------|---------------|///////////|-------------|///////////|----------------|

r: 0 0.2 0.21 0.32 0.345 0.425 0.525

ρ: 0.05 20 6 20 6 20

FIGURE 5. Geometry of a two-cascade target

For a one-cascade target [10] it was numerically shown that the minimum energy, which should be embedded in the area having mass m_2 for the target to “catch fire”, is equal to 2.1. The two-cascade target also burns at this energy. It has the value of extraction of energy (E_{ext}) by the working area 27.3 times higher than in the one-cascade target. The identical amount of the emitted energy E_{emit} and the coefficient of amplification $K = E_{ext} / E_{emit} = 16.6$ are explained by the fact that practically all deuterium burned out. But for the two-cascade target it is enough to embed 1.5 energy units in both areas for the target to “catch fire”. It has higher value of extraction of energy (E_{ext}) by the working area than in the one-cascade target in which more energy was embedded (2.1). The amount of the emitted energy E_{emit} is less than in the one-cascade target, but the coefficient of amplification $K = E_{ext} / E_{emit} = 21.6$ is higher (Table 2).

TABLE 2. Results of extraction of energy by the working area for one-cascade and two-cascade targets

Embedded energy E_{emb}	**One-cascade target**			**Two-cascade target**		
	E_{ext}	E_{emit}	K	E_{ext}	E_{emit}	K
2.1	0.0436	34.78	16.56	1.19	34.87	16.6
1.5				0.174	32.35	21.6

CONCLUSIONS

The received results show advantages of a two-cascade target compared to a one-cascade one:

- in a two-cascade system, the extraction of energy by the working area increases compared to a one-cascade one what determines a better burning of a DT layer and a bigger energy yield as a result of thermonuclear reactions;
- in a two-cascade system, the amount of the embedded energy for firing the target decreases.

ACKNOWLEDGEMENT

The results received during implementation of the project No. 9.1.02.2015 within the Program "D. I. Mendeleyev's scientific fund of Tomsk State University" in 2015 were used in the paper.

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