Laser and Particle Beams (2003), *21*, 81–84. Printed in the USA.

DOI: 10.1017/S0263034603211150

Deuterium targets and the MDMT code

A.G. AKSENOV AND M.D. CHURAZOV
Institute of Theoretical and Experimental Physics, Moscow, Russia

(RECEIVED 26 May 2002; ACCEPTED 17 June 2002)

Abstract

By means of a new two-dimensional three-temperature hydrodynamical code we considered the burning of the deuterium fuel with a small amount of a catalytic ^{3}He in a cylindrical channel. To reduce the requirements for an ignition heavy ion beam we used an irradiated DT tablet ($J_{beam} = 4 \cdot 10^6$ TW/g, $E_{beam} = 0.5$ MJ). We received the steady burning wave for the parameter $\rho r \gtrsim 8$–10 g/cm^2 with a gain coefficient $G \gtrsim 30$ in comparison with such parameters for the DT fuel $G \sim 140$ at $\rho r = 0.5$ g/cm^2. Upon reducing the parameter $\rho r \sim 4$ g/cm^2, the burning wave disappears moving along a channel. A part of the deuterium fuel burns with a reduced gain coefficient of 3–5. In the case of large fuel densities $\rho = 100$ g/cm^3, our estimates show extremely large requirements for a compression beam 450–750 MJ for $\rho r \sim 4$ g/cm^2.

Keywords: Burn performance; Deuterium fuels; Numerical simulations

1. INTRODUCTION

The DT fuel heavy ion fusion (HIF) conception for a cylindrical target was analyzed in detail in the HIF2002 symposium (Basko *et al.*, 2002). This is a cylindrical inertial target with a direct irradiation. In the compression stage, the fuel is compressed by a heavy shell moved into a symmetry axis due to the energy of a hollow beam deposited in a absorber shell. In the next stage the compressed fuel is ignited by another beam. The ground parameters of the energetic system for the DT project are presented in Table 1 (see also Fig. 1). The requirements for a compression beam for a cylindrical target are similar to those parameters for an indirect spherical target. The parameters of an ignition beam are now seen as enormous. Nevertheless the theoretical investigation of cylindrical targets can be useful. Probably the Rayleigh–Taylor instability problem for such a target has a simpler solution than this problem for an indirect spherical target with converters because of the possibility of receiving a high initial symmetry of a target and an adequate symmetry of a compression beam.

The next logical question would be about the analogous parameters for the cylindrical target with a deuterium fuel. Today there is no an acceptable positive conclusion for the deuterium target even in the case of a very hard deuterium project. There are some almost negative conclusions about the burning of a deuterium fuel channel (Feoktistov, 1998), while Atzeni and Ciampi (1999) made more positive conclusions for a deuterium fuel. More complex regimes for the deuterium burning were estimated by Linhart (1993) and Bilbao *et al.* (2001). We investigate the burning of the deuterium fuel in the cylindrical target. To reduce the burning temperature we introduced a small amount (10% of the ions) of a catalytic ^{3}He into a fuel. To keep the same parameters for an ignition beam we used the deuterium tritium tablet irradiated by an ignition beam.

The possibility of burning in the target at different densities in inertial fusion can be estimated by the parameter ρr. This parameter indicates whether the reaction rate is enough for the burning during the character hydrodynamical time of

Address correspondence and reprint requests to: A.G. Aksenov, Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya, 25, 117259 Moscow, Russia. E-mail: alexei.aksenov@itep.ru

Table 1. *Parameters of DT target*

	Stage	
Parameter	Compression	Ignition
ρ_{fuel}, g/cm^3	0.225	100
r_{fuel}, cm	0.105	0.005
$(\rho r)_{fuel}$, g/cm^2		0.5
ρ_{shell}, g/cm^3	11.4	1000
r_{shell}, cm	$\sim$0.14	0.015
z_{max}, cm	1	
$(\rho l)_{beam}$, g/cm^2	6	
J^{max}_{beam}, TW/g	$\sim$300	$4 \cdot 10^6$
time, ns	$\sim$100	0.2
E_{beam}, MJ	$\sim$7	0.4
G	$\sim$140	

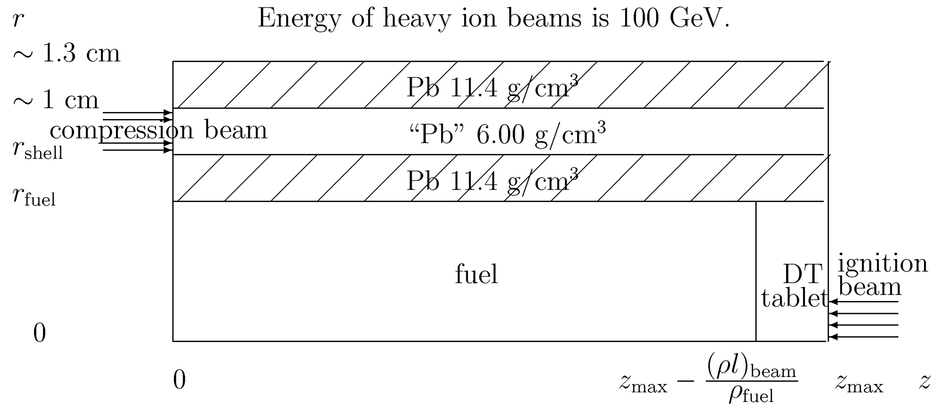

Fig. 1. Scheme of cylindrical targets.

the fly away. It can be noted that the massive shell can considerably increase the time of the existence of the fuel at high density even for a small parameter ρr. For the character density 100 g/cm^3 and the time $\lesssim$1 ns, the ion temperature $T_i \sim 10^8$ K is sufficient for a fast burning of the DT fuel. At such temperatures (if the radiation temperature can reach the ion temperature) the radiation energy ($\propto T^4$) is only a little part of the total energy in comparison with ion and electron energies ($\propto T$ in an ideal gas EOS approximation). In the optically thin regime, the radiation losses have the weak influence of a burning regime in a DT fuel. The burning of a deuterium fuel for selected parameters $\rho \gtrsim 100$ g/cm^3, $t \lesssim 1$ ns has an appropriate rate only for the ion temperature $T_i \sim 10^9$ K. At such temperatures and densities, the equilibrium ($T_i \sim T_e \sim T_r$) is established during a short time. Then the radiation energy becomes the main part of the total energy. The loss of radiation can stop the burning along a channel. Whether the region is optically thin or thick for a radiation also can be estimated by the optical path parameter ρr. Computational simulations are required to estimate the burning in the target with a deuterium fuel.

In this work, the new multidimensional multitemperatures code (MDMT) was employed to obtain basic parameters of the deuterium energetic system in a cylindrical target. This is a Eulerian Godunov type code (see details in the work by Churazov *et al.*, 2001). We used the two-dimensional approximation (with independent variables r, z in a cylindrical coordinate system) and three temperatures for ions, electrons, and radiation. Radiation and electron transfers are considered in a diffusion approximation with flux limiters. Instead of the diffusion of charged particles, the local energy deposition is adopted. In some calculations, the diffusion of α particles is included. Neutrons are disregarded. The ideal gas law equation of state with $\gamma = \frac{5}{3}$ for ions and electrons is used. Kinetic coefficients have been taken from one-dimensional Deira3 code by Basko (1990).

2. BURNING IN THE DEUTERIUM CHANNEL

First of all we considered the common problem about the burning in a compressed deuterium channel. The scheme used is the same scheme as for a DT target (Table 1) but for different scaled densities of a fuel and an envelope. In some calculations we fixed densities but changed the length scale. The DT tablet irradiated by ions is used for a deuterium ignition at comparatively low requirements for the ignition beam. We obtained the following results:

- the burning regime is characterized mainly by the parameter ρr;
- at a stationary burning temperatures T_i, T_e, T_r are in an equilibrium except some zone around the burning front;
- there is a stationary regime with a detonation for the parameter $\rho r \gtrsim 8$–10 g/cm^2 (see Fig. 2);
- for $\rho r \lesssim 4$ g/cm^2 the burning disappears during the moving of a burning wave along the channel due to radiation losses, but some part of the deuterium fuel is burned due to a massive envelope.

These are expected results. The density after a shock wave is less then $4\rho_{\text{fuel}}$ because of the reducing of an average density in the channel cross section before a burning front due to radiation heat. At a density $\rho r = 5$ g/cm^2, the optical path for photons is close to 1 for Compton scattering.

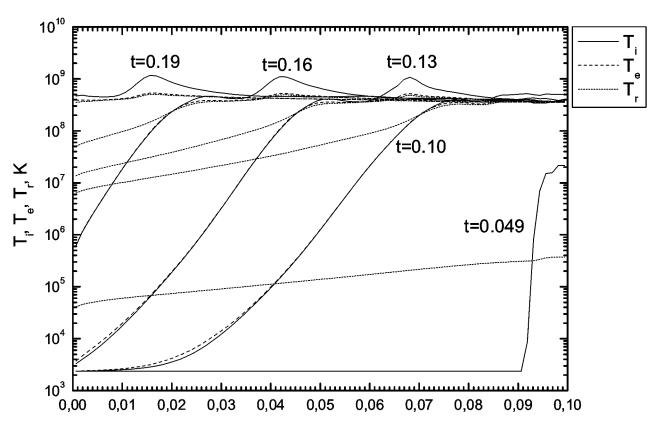

Fig. 2. The existence of a steady solution for large $\rho_{fuel} = 2000$ g/cm^3 ($\rho r = 10$ g/cm^2) in a deuterium channel. Temperature profiles at different moments in a symmetry axis (t in nanoseconds).

https://doi.org/10.1017/S0263034603211150 Published online by Cambridge University Press

Table 2. *Parameters of deuterium target*

	Stage	
	Compression	Ignition
Parameter	Initial → received	Adopted values
ρ_{fuel}, g/cm^3	0.16 → 100	100
r_{fuel}, cm	0.561 → 0.023	0.04
$(\rho r)_{\text{fuel}}$, g/cm^2		4
ρ_{shell}, g/cm^3	11.4	1000
r_{DTtablet}, cm,		0.005
r_{shell}, cm	0.63	0.16
$z_{\max}$, cm	1	
$(\rho l)_{\text{beam}}$, g/cm^2	6	
$J_{\text{beam}}^{\max}$, TW/g	1230	$4\cdot 10^6$
time, ns	250	0.2
E_{beam}, MJ	250	0.4
G	3–5	

3. CYLINDRICAL DEUTERIUM TARGET

There are two significant moments in comparison with previous works (Churazov & Sharkov, 1993; Atzeni *et al.*, 1998). We adopted the possibility to employ the target with the big energy output $E_{\text{out}} \geq 3$ GJ. It is not necessary to use a magnetic insulation if $\rho r \geq 2$–4 g/cm^2. A big energy input with the scale ∼450–750 MJ was employed to obtain the effective compression of this big target. As an example of this compression, the set of results is shown in Table 2.

A cryogenic cylindrical target was considered to obtain the fuel density $\rho \sim 100$ g/cm^3 and the target parameter $\rho r \gtrsim 2$–4 g/cm^2. The scheme of this target is shown in Figure 1. The beam rotates around the target axis with period sufficient to obtain a good axial compression symmetry. The special form of the energy input was introduced at the compression stage of the target $J_{\text{beam}}(r,t) = 12.3\cdot 10^{14}(t/10^{-8}\text{ ns})^5[\text{erg}/(\text{g}\cdot\text{s})]$ in the "lead" shell with a density $\rho = 6$ g/cm^3. In one-dimensional calculations of a compression stage by Basko (1990) Deira3 code we received in the final stage the average value of a fuel density $\rho_{\text{fuel}} = 100$ g/cm^3 and a fuel radius $r_{\text{fuel}} = 0.023$ cm at expanses of beam energy 250 MJ (Table 2). Probably the optimization of the target illumination may be employed to decrease the compression energy. For instance, the level $E_{\text{beam}} \sim 100$ MJ was considered by Koshkarev (1989) as a complex, but a real task for the accelerator technics. The works about an adiabatic compression (Dolgoleva & Zabrodin, 1999) may be used for solving of such a problem.

For the two-dimensional simulation, we have taken the received average fuel density but we adopted a bigger fuel radius $r_{\text{fuel}} = 0.04$ cm^3 than a received radius $r_{\text{fuel}} = 0.023$ cm^3 while increasing the estimated beam energy for a compression stage $E_{\text{beam}} = 450$–750 MJ. Calculations show the existence of a burning wave along a part of a target (see Fig. 3) before the ion temperature is reduced to some units of 10^8 K. During this time part of the deuterium fuel is burned. The received gain coefficient can be estimated as 3–5.

For parameters $r_{\text{fuel}} = 0.08$ cm and $\rho r = 8$ g/cm^2 estimates give the gain coefficient as about 30.

4. CONCLUSIONS

Our two-dimensional calculations show the existence of a stationary burning in the deuterium cylindrical targets for parameter $\rho r \gtrsim 8$–10 g/cm^2 with an attractive gain coefficient of ∼30 and the total energy output of ∼30 GJ. The lower level of energy can be reached only for very high density $\rho_{\text{fuel}} \gtrsim 1000$ g/cm^3. But the possibility of receiving such densities remains unknown.

The reduction of the parameter ρr to a value of ∼4 g/cm^2 allows for burning of part of the fuel but with a little gain coefficient estimated as 3–5 for $\rho_{\text{fuel}} = 100$ g/cm^3. There is an open question about the optimization of a compression for reducing the deposited energy.

In an example of the target design we are developing, a new MDMT code is presented that also require such improvements as the introduction of diffusion equations for all charge particles (protons), the spectral radiation diffusion, and probably a neutron transport. Also our code requires some optimization for the reducing of calculation time. By means of this code it is possible to consider such important multidimensional problems as the Rayleigh–Taylor instability and a mixing of a fuel and a shell in a compression stage.

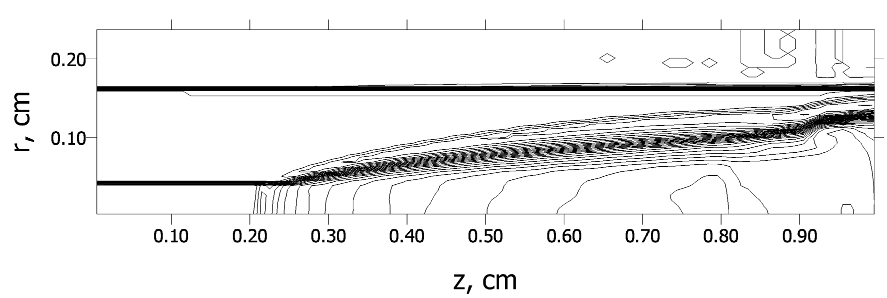

Fig. 3. Density profiles at $t = 1.5$ ns. $\lg \rho_{min} = 0.9$, $\lg \rho_{max} = 3.6$, $\Delta \lg \rho = 0.1$.

https://doi.org/10.1017/S0263034603211150 Published online by Cambridge University Press

REFERENCES

Atzeni, S. & Ciampi, M.L. (1999). Potentiality of tritium-pool fuels for ICF fast ignitors. *Fusion Eng. Des.* **44**, 225–231.

Atzeni, S., Temporal, M., Piriz, A.R., Basko, M.M., Maruuhn, J., Lutz, K.-J., Ramis, R., Ramirez, R., Honrubia, J. & Meyer-ter-Vehn, J. (1998). Report of the European Study Group on Heavy Ion Driven Inertial Fusion for the period 1995–1998. The HIDIF Study, GSI-98-06 Report, 161–176.

Basko, M.M. (1985). Equations of One-Dimensional Radiative Hydrodynamics with Heat Conduction and Kinetics of Thermonuclear Burn. Preprint ITEP-145, *Inst. of Theor. Exp. Physics*. Moscow (in russian).

Basko, M.M., Churazov, M.D. & Aksenov, A.G. (2002). Prospects of heavy ion fusion in cylindrical geometry. *Laser Part. Beams* **20**, 411–414.

Bilbao, L., Bernal, L., Linhart, J.G. & Verru, G. (2001). DT ignition in a Z pinch compressed by an imploding liner. *Nucl. Fusion* **41**, 1551.

Churazov, M.D., Aksenov, A.G. & Zabrodina, E.A. (2001). The ignition of thermonuclear targets by means of the heavy ion beam. Voprosy Atomnoi Nauki i Techniki. *Matem. Model. Fiz. Prozsessov* **1**, 20–28 (in russian).

Churazov, M.D. & Sharkov, B.Yu. (1993). Heavy-ion fusion targets without tritium. *Nuovo Cimento* **106A**, 1945–1948.

Dolgoleva, G.V. & Zabrodin, A.V. (1999). The strokeless compression of microtargets. Preprint *Keldish Inst. Applyed Math*., Mowcow. 53 (in russian).

Feoktistov, L.P. (1998). Thermonuclear detonation. *Physics-Uspekhi* **41**, 1139–1147.

Koshkarev, D.G. (1989). Heavy ion driver for fast ignition. HIF2002 abstracts.

Linhart, J.G. (1993). Propagation of fusion detonation in cylindrical channels. *Nuovo Cimento* **106A**, 1949–1958.

https://doi.org/10.1017/S0263034603211150 Published online by Cambridge University Press