Laser and Particle Beams (2002), *20*, 415–418. Printed in the USA.

DOI: 10.1017/S0263034602203092

Fast ignition of the DT fuel in the cylindrical channel by heavy ion beams

V.V. VATULIN AND O.A. VINOKUROV
RFNC-VNIIEF, 607190, Sarov, Nizhny Novgorod Region, Russia

Abstract

The so-called *fast ignition* mode is one way to ignite the thermonuclear fuel in systems of inertial fusion and decrease of the necessary energy of the driver. In the present work the second stage of the process—the heating, the thermonuclear burning initiation under the influence of a powerful ion pulse, and distribution of the burning all over the rest of the cylindrical system—is studied. The main purpose of the presented calculations was to determine the threshold of the fast ignition of the cylindrical DT cord by a heavy ion beam.

1. INTRODUCTION

In the present concept, the necessary ion flux energy for the systems with a heavy ion driver at the traditional irradiation mode is 5–10 MJ with the ion flux intensity on the converters up to 1000 TW/cm^2 and more (Bangerter, 2001; Vatulin *et al.*, 1999). The *fast ignition* mode is one of the methods applied to decrease the necessary initial portion of the driver energy (Tabak *et al.*, 1994). In this case, the thermonuclear area is compressed by the initial portion of the driver energy to high densities at a comparatively low ion temperature (it is assumed that it will demand a not very high driver energy). At the second stage, a portion of the thermonuclear fuel is heated in a short period of time by a powerful pulse (ion, laser, etc.). In this DT area, the thermonuclear burning is initiated, which later will spread all over the thermonuclear fuel.

In the present work, the second stage of the process is studied. The main aim of the calculations was to determine the threshold of the fast ignition of a cylindrical DT cord by a heavy ion beam.[1] The calculations were carried out at the two-dimensional setting with the MIMOZA-ND complex (Sofronov *et al.*, 2001). The following physical processes were calculated: the two-temperature gas dynamics; X-ray energy transfer at the multigroup spectral diffusive approximation; electron thermal conductivity; energy exchange between electrons, ions, and the radiation; α-particle energy transfer along the space at the multigroup diffusive approximation, and some others.

Address correspondence and reprint requests to: V.V. Vatulin, RFNC-VNIIEF, 607190 Dzerzhinksy str., 102, Sarov, Russia. E-mail: vatulin@vniief.ru

[1]The initial state of the system is proposed by the Institute of Theoretical and Experimental Physics specialists B.Yu. Sharkov, M.M. Basko, M.D. Churazov, and G.D. Koshkarev. The possibility of realizing this state is discussed in Basko *et al.* (2002).

2. SETTING OF THE TWO-DIMENSIONAL CALCULATIONS OF THE FAST IGNITION OF THE DT CORD

The calculations were carried out in the two-dimensional geometry (X, Y)—see Figure 1. A beam of Bi^{209} ions was set as the energy (at the left side). The ion energy in the beam was $E_1 = 100$ GeV, the ion stopping range was $(\rho l) \sim 6$ g/cm^2 (Ziegler, 1980). The total beam energy and DT-gas density in the target were varied during the determination of the threshold of formation of a stationary burning wave. In the calculations, the power of the beam was assumed to be constant at the radius and in time at all the pulse durations ($\tau = 0.2$ ns). The energy in the DT area at the ion flux stopping was released in electrons according to the function of ion stopping, presented in Table 1 (Ziegler, 1980).

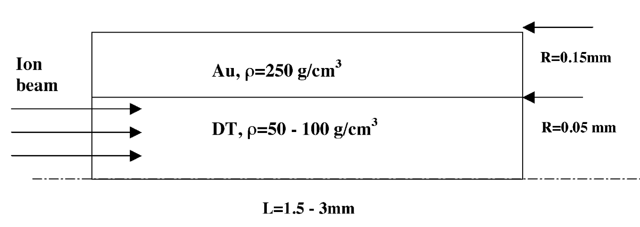

Fig. 1. Scheme of the target in the integrated two-dimensional calculations.

Table 1. *Dependence of the energy release in the DT gas at the Bi^{209} stopping on the ion energy.*

E (GeV)	0	0.1	0.5	1	1.3	3
dE/*dx* (MeV/mg/cm^2)	0	26	51	56.6	57.2	55.3
E (GeV)	5	10	20	30	50	70	100
dE/*dx* (MeV/mg/cm^2)	48.8	37	25.8	20.7	15.7	13.3	11.4

3. RESULTS OF THE CALCULATIONS

A wave of thermonuclear burning is to form in the DT cord at the maximum taken in the calculations parameters (the density DT ~ 100 g/cm^3, ion beam energy ~ 400 kJ). In Figure 2, the gas density distribution at the target axis at the moments of time 0.1, 0.2, 0.25 ns is presented. It was unexpected that a zone of reduced density forms before the shock wave in the gas because of the heating by hard X rays from the zone of thermonuclear burning. The ion temperature was ~100 keV, the maximum density ~400 g/cm^3 (Figs. 2, 3). Thus, a stationary wave of burning, propagating at a speed of ~0.25 cm/ns formed in the target. The forming of a stationary mode of burning is also visible in Figure 4, where the dependence of the number of DT reactions $N_{DT}(t)$ on time is presented. From ~0.2 ns, the rate of the thermonuclear reactions appears to be virtually constant and constitutes ~2.5·10^{20} 1/ns. By 0.4 ns, DT burning out was ~50% (maximum value); the energy release due to the DT reactions was ~14 MJ.

A series of calculations with cut ion beam and target parameters was carried out to analyze the stability of the obtained data. The parameters of these calculations are presented in Table 2. In neither of the investigated variants did the initiation of the stationary wave of the thermonuclear burning take place. Thus, the nominal target and ion beam parameters turned out to be close to the threshold values, leading to the initiation of the thermonuclear detonation. In Table 2, the integral results of these calculations are presented. In Figure 4, the dependence of the number of DT reactions on time is presented for variants 4 and 5. The dependence $N_{DT}(t)$ were close to each other for the systems with different initial densities until ~0.1 ns, that is, they are determined mainly by the heating by an outer source. In the system with the initial density 100 g/cm^3, from ~0.1 ns a self-sustaining thermonuclear reaction starts, while at lower densities, the thermonuclear burning stops practically immediately after the outer heating has ceased. In the case of the lower ion pulse energy, the differences in $N_{DT}(t)$ take place from the very beginning of the process.

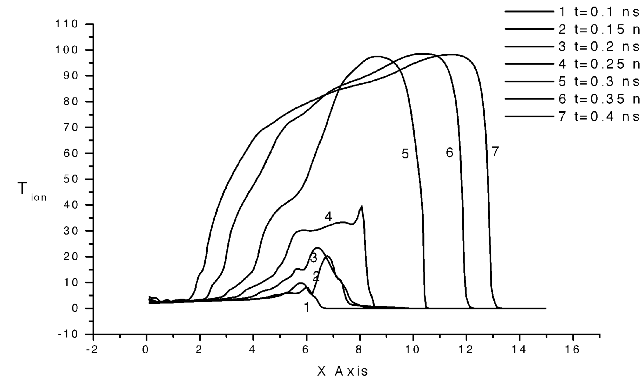

Fig. 3. Ion temperature distribution along the target axis in the area of the thermonuclear burning at different points of time.

4. POSSIBILITY OF LOWERING THE DEMANDS TO THE TARGET AND PULSE PARAMETERS

A question arises: Can the necessary target and ion beam parameters be somehow lowered? There are several hypothetical possibilities.

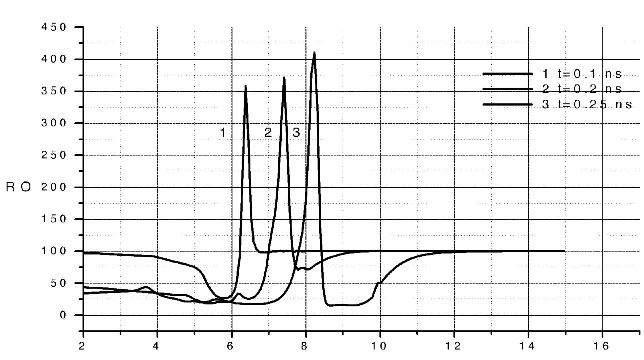

Fig. 2. DT-area density distribution along the target axis at different points of time.

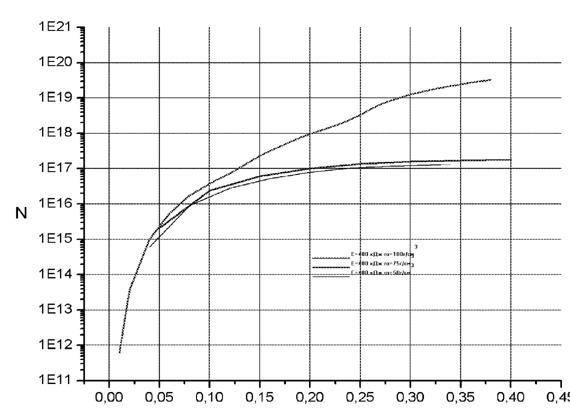

Fig. 4. Number of the DT-reactions depending on time at the varied initial density; 1: $\rho_0 = 100$ g/cm^3, 2: $\rho_0 = 75$ g/cm^3, 3: $\rho_0 = 50$ g/cm^3.

https://doi.org/10.1017/S0263034602203092 Published online by Cambridge University Press

Table 2. *Ion beam and target parameters in the calculations of the initiation of a cylindrical beam and major calculations results.*

No.	Beam energy (MJ)	Average value of the energy release (MJ/g)	Initial DT density (g/cm^3)	Ion stopping range (mm)	Maximum DT density (g/cm^3)	Maximum DT temperature (keV)	Number of the DT reactions, 10^{19}
1	0.4	850 (2500 max)	100	0.6	400	100	3.5
2	0.2	425	100	0.6			$1.2 \cdot 10^{-3}$
3	0.3	640	100	0.6	400	~6	$5 \cdot 10^{-3}$
4	0.4	850	50	1.2			$1.3 \cdot 10^{-2}$
5	0.4	850	75	0.9	300	9	$1.8 \cdot 10^{-2}$

4.1. Application of a spin-polarized thermonuclear fuel

In a row of theoretical works, the possibility of increasing the cross sections of several thermonuclear reactions in a spin-polarized thermonuclear fuel was predicted. In Kurlrud *et al.* (1982), a possible influence of the cross-sectional increase on the thermonuclear target parameters are studied for inertial fusion. The calculations of the conditions of the thermonuclear burning wave formation in the fast ignition mood (Fig. 1, the target) at the increase of the DT reaction cross section for 50% were carried out. Under such an assumption, the DT-gas density threshold on the ignition comes down 1.5-fold.

4.2. Decrease of the ion stopping range in plasma

4.2.1. The decrease of the ion stopping range

The decrease of the ion stopping range at the plasma temperature increase is forecast in some theoretical research. The experiments in this direction are held with the application of different methods of plasma heating (e.g., Golubev *et al.*, 1999). The forthcoming experiments at the Phelix-Unilac facility with the application of a X-ray target (Vasina & Vatulin, 2000) and the corresponding theoretical analysis will permit defining this phenomenon more exactly.

4.2.2. Changing the ion stopping range due to the ion beam polarization

The ion polarization leads to sufficient changes of the cross sections of the nuclear process (Baldin, 1958). The research on these processes refers mainly to the area of ion energies about hundreds of MeV/A and higher and the influence of the polarization on nuclear processes. It may be useful to organize the research of the processes in the area of energies up to 100 MeV/A.

4.2.3. The plasma polarization

The plasma polarization also can change considerably the process of the outer ion flux stopping. At the interaction with the medium, intense particle or optical radiation fluxes orient the spins of the plasma particles (so called dynamic polarization). The process laser beam–matter interaction might be responsible for the anomalous decrease of ion energy loss in the GSI experiments on the ion stopping in flat targets at the Phelix-Unilac complex (Roth *et al.*, 1998). If the hopes are justified and the increase of the cross section of the ion flux–plasma interaction, in particular, at its irradiation by laser irradiation, is possible, the *combined* laser–ion target can be presented. The possible schemes of that target are shown in Figure 5. In this case, the intensity of the influence of the ion flux of several hundreds of TW/cm^2 might turn out to be sufficient for the X-ray generation.

5. CONCLUSION

The results of the calculations shown in the present work demonstrate the principal possibility of the thermonuclear burning wave initiation in cylindrical DT-targets under the influence of an ion pulse in the fast ignition mode. The calculations were carried out at the idealized setting. In particular, the problem of the possibility of the DT-cord compression up to such densities (the degree of compression $R_0/R_{fin} \approx 20$ when a condensed fuel is used and $R_0/R_{fin} \approx 60$ for the DT-gas) remains open. The effect of mixing gold into the DT-fuel to counter Rayleigh–Taylor instability during compression and burning was not investigated. Therefore the obtained results should be treated as the illustration of the processes, following such a burning mode.

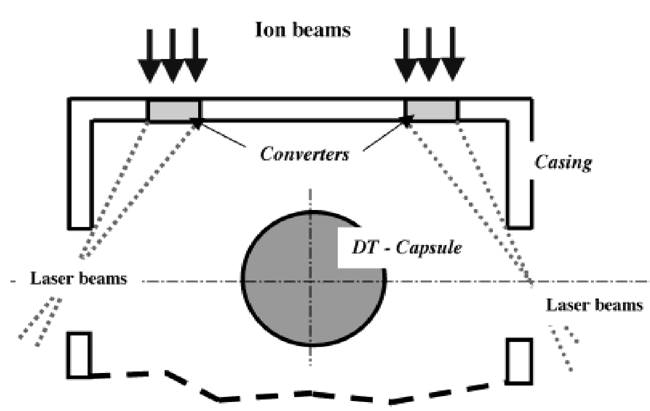

Fig. 5. Principal schemes of the indirect heavy ion–laser target for ICF.

https://doi.org/10.1017/S0263034602203092 Published online by Cambridge University Press

ACKNOWLEDGMENTS

The work was carried out in the frame of the ISTC Project #1137 and WTZ 01/694.

REFERENCES

Baldin, A.M. (1958). Optical anisotropy of the atomic nuclei. *Nucl. Phys*. **9**, 237–251.

Bangerter, R. (2001). Heavy ion fusion program in the USA. *NIMA*, Section A, Vol. 464, No. 1–3, pp. 17–23.

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

Golubev, A., Turtikov, V., Fertman, A., Roudskoy, I., Sharkov, B., Gießel, M., Neuner, U., Roth, M., Taushwitz, A., Wahl, H., Hoffmann, D.H.H., Funk, U., Süß, W. & Jacoby, J. (1999). Experimental investigation of charge state distribution and energy loss of swift ions in capillary plasma target. *High Energy Density in Matter Produced by Heavy Ion Beams*, p. 11. Darmstadt, Germany: GSI.

Kurlrud, R.M., Furth, H.P., Valeo, E.J. & Goldhaber, M.K. (1982). Fusion reactor plasmas with polarized nuclei. *Phys. Rev. Lett*. **49**, 1248–1251.

Roth, M., Bock, R., Geissel, M., Hoffmann, D.H.H., Iwase, O., Stockl, C., Suss, W. & Seelig, W. (1998). Stopping power in laser produced plasmas. *High Energy Density in Matter Produced by Heavy Ion Beams*, p. 7. Darmstadt, Germany: GSI.

Sofronov, I.D., Bel'kov, S.A. & Vinokurov, O.A. (2001). MIMOZA code. In a collection Trudy VNIIEF, pp. 101–104. Sarov, Russia: VNIIEF.

Tabak, M., Hammer, J., Glinsky, M., Kruer, W., Wilks, S., Woodworth, J., Campbell, E., Perry, M. & Mason, R. (1994). Ignition and high gain with ultrapowerful lasers. *Phys. Plasmas* **1**, 1626–1634.

Vasina, E. & Vatulin, V. (2000). Experimental scheme for investigation of ion stopping in plasma-indirect laser target design. *High Energy Density in Matter Produced by Heavy Ion Beams*, p. 52. Darmstadt, Germany: GSI.

Vatulin, V, Afanas'eva, V., Basin, A., Eliseev, G., Ermolovich, V., Jidkov, N., Karepov, V., Kharitonov, A., Skrypnik, S., Shagaliev, R., Vasina, E. & Vinokurov, O. (1999). Indirect fusion targets for heavy ion driver scenario. *Proc. First Int. Conf. on Inertial Fusion Science and Application*, Bardeaux, Septermber 12–17, pp. 503–508.

Ziegler, J.F. (1980). *Handbook of Stopping Cross Sections for Energetic Ions in All Elements*. New York: Pergamon.