

OVERVIEW OF DIRECTLY DRIVEN HIF TARGETS

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The results of optimization in several classes of spherical DT and D_2 targets driven by heavy ion beams are reported. It was found that, in the class of simple single-shell two-layer DT targets, the energy gains $G \simeq 100$ can be reached—provided that the beam power $P_{in} \gtrsim 700$ TW. Optimization in a more sophisticated class of DT targets with a low-Z absorber layer has revealed that, with a 700 TW box-shaped pulse of 10-GeV Bi ions, spark ignition can be achieved, which results in the optimum energy gain of $G \simeq 400$. For single-shell D_2 targets driven by a time-profiled 100-MJ pulse of 12-GeV Bi ions with a peak power of 10^4 TW, a maximum gain of $G = 10$ was obtained.

Two examples of non-one-dimensional directly driven targets are discussed—a quasi-spherical DT target illuminated by a cylindrically symmetric ion beam, and a cylindrical D_2 target with magnetically suppressed electron thermal conductivity in the fuel. The energy gain of the latter can be higher than the above-quoted limit $G = 10$ for spherical D_2 targets.

1 INTRODUCTION

In directly driven thermonuclear targets the energy of fast heavy ions is converted directly into the internal energy of the absorber layer, and the ensuing high pressure drives the target pusher to an implosion velocity of $> 10^7$ cm/s. The imploding pusher compresses and heats up the thermonuclear fuel to the very point of ignition. As a first step on the way to understanding the prospects of heavy ion beam fusion, it appears quite natural to explore the directly driven targets within the framework of one-dimensional treatment, under the simplifying assumption of perfectly spherical illumination. Since perfectly spherical illumination will hardly ever be achieved, the results of such a study should be considered as being fiducial theoretical propositions and values that might serve as guidelines when designing realistic targets for heavy ion beams.

Below we present the results of optimization studies for three different types of spherically-symmetric directly driven heavy ion beam targets. As a basic set of driver parameters, the values $E_{in} = 6.12$ MJ (the beam energy), $t_{in} = 17$ ns (the pulse duration) and $E_b = 20$ GeV (the energy of ^{209}Bi ions in the beam)—as proposed by the ITEP (Moscow) group¹—have been used. Further, conceivable approaches on the way to reconcile a non-spherical illumination geometry with the concept of direct drive are illustrated with the two examples of non-one-dimensional targets:

1) a spherical target surrounded by a shell whose thickness is adjusted so as to compensate for polar angle variations in the penetration depth of illuminating ions; and

2) a cylindrical target with a strong magnetic field which suppresses the transverse electron thermal conductivity, as well as the energy losses by charged products of nuclear reactions.

2 SIMPLE SPHERICAL DT TARGETS

First of all, we have investigated one of the simplest types of spherical deuterium-tritium targets, with a single solid shell which consists of only two different layers (see Figure 1). The internal layer is the equimolar DT mixture in a solid state. The external layer is supposed to be made of a heavy metal and serves both as an absorber for the ion beam (the outer part of the layer) and as a pusher for the DT fuel (the inner part of the layer). We assume that the spherical cavity inside the solid shell is filled with the DT gas whose density is treated as a free parameter of the target.

It is assumed also that simple targets are irradiated by ion pulses with the simplest box-shaped time profile, the beam power being constant within the time interval $0 < t < t_{in}$. The spatial distribution of the specific deposition power has been calculated according to the full-scale theory of ion stopping in materials with temperatures and densities varying in time and space.

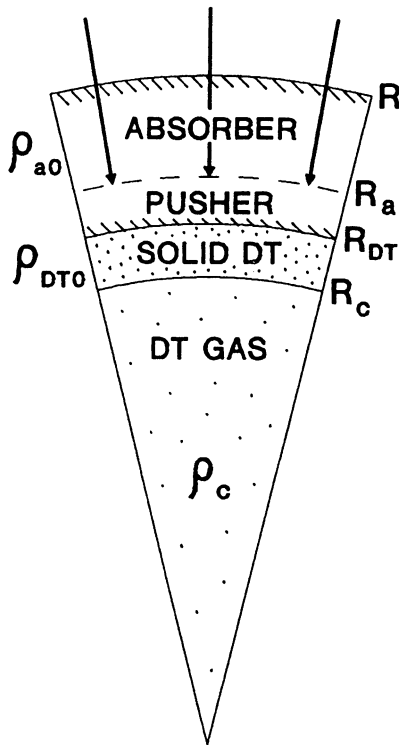


FIGURE 1 Schematic view of a simple spherical DT target.

Thus, a simple target is characterized by the following seven free parameters.

Driver parameters:

- E_{in} —the total beam energy injected into the target
- t_{in} —the ion pulse duration
- E_b —the energy of individual ions in the beam

Target parameters (see Figure 1):

- R —the outer target radius
- R_{DT} —the outer radius of the solid DT layer
- R_c —the radius of the central cavity
- ρ_c —the density of DT gas in the cavity

The material of which the outer layer of the solid shell is made, and the sort of illuminating ions (^{209}Bi), are supposed to be chosen beforehand and fixed. The problem of optimization has been stated and solved as follows: for a fixed set of driver parameters we are to find the maximum of the energy gain G as a function of the four free target parameters.

Optimization in the class of simple targets has been carried out with the one-dimensional two-temperature hydrodynamic code GITTAM, in which separate temperatures for matter and radiation are assumed. In the equation of state and in the transport and relaxation coefficients realistic properties of materials have been accounted for. Alpha particles were treated locally, and an approximate method to evaluate the non-local heating of the DT fuel by 14-MeV neutrons has been employed.

Table 1 lists the energy gains G of a number of optimum targets from the class under consideration. Typical values of the initial radius for the optimum targets fall in the range $R = 2.5\text{--}3$ mm; the fuel mass $M_{DT} = 1\text{--}2$ mg. Typical values of the hydrodynamic efficiency η and of the beam-to-fuel coupling efficiency η_f are 0.1–0.15 and 0.03–0.05, respectively.

In the parameter region studied, simple DT targets exhibit the following common feature: if such a target ignites, it ignites always uniformly over the entire fuel mass; the case of spark ignition has never been observed. At maximum compression, typical parameters of the uniform fuel sphere are $\langle \rho r \rangle_{DT} = 2.5 - 3$ g/cm², $T_{DT} \simeq 1.7$ keV. A comparatively low ignition temperature is stipulated by the presence of a massive high-Z pusher that locks up the radiation inside the fuel.

Summarizing the results presented in Table 1, we arrive at the following conclusions concerning the performance of simple DT targets.

TABLE 1
Energy gains of the optimum simple DT targets

E_{in} , MJ	6.12	6.12	6.12	6.12	6.12	6.12	6.12
P_{in} , TW	360	720	360	720	360	720	720
E_b , GeV	20	20	10	10	20	20	10
Absorber	Au	Au	Au	Au	Pb	Pb	Pb
G	54	85	55	94	23	37	76

1) For the input energy $E_{in} \simeq 6$ MJ, energy gains of $G \simeq 80$ –100 can be achieved within the framework of the uniform ignition pattern.

2) For efficient performance of simple DT targets at $\simeq 6$ MJ of input energy, the beam power $P_{in} = E_{in}/t_{in} = 360$ TW is too low: a twofold increase in P_{in} makes the energy gain rise from $G \simeq 50$ to $G \gtrsim 80$; it is useless, however, to increase the beam power any further, beyond $P_{in} \simeq 1000$ TW, because it does not help to get beyond the gain values $G \simeq 100$ –110.

3) For targets with the gold absorber, the ^{209}Bi ion energy $E_b = 20$ GeV is almost as good as $E_b = 10$ GeV; for targets with the absorber of lead the ion energy $E_b = 20$ GeV results in unacceptably low gain values.

And finally, it should be noted that the tow-temperature code GITTAM is not quite adequate for the stage of strong thermonuclear burning. Nevertheless, as demonstrated by later simulations with the three-temperature code DEIRA, the values of the thermonuclear gain G as calculated with GITTAM are quite close to those obtained with DEIRA.

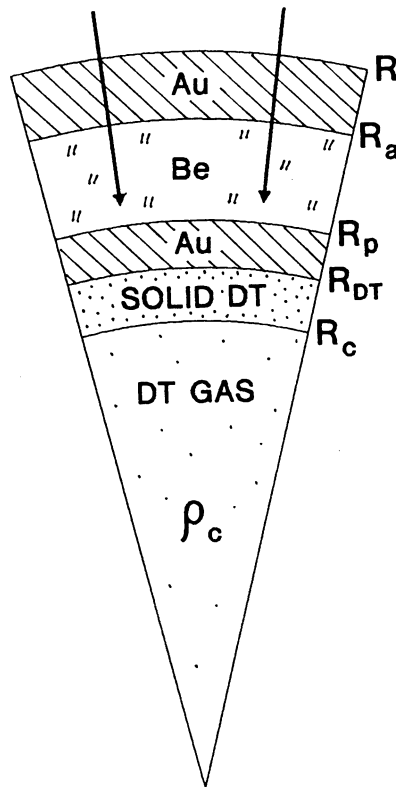


FIGURE 2 Schematic view of a spherical DT target producing high energy gain.

3 SPHERICAL DT TARGETS OF HIGH GAIN

To look for heavy ion beam targets with higher energy gains, in which the spark ignition of DT fuel occurs, we have explored a class of more sophisticated single-shell targets, with a low-Z intermediate layer introduced into the absorber (see Figure 2). In general, addition of such a layer leads to a considerable rise in the values of the hydrodynamic efficiency of targets driven by the beams of charged particles². The same simple box-like shape was assumed for the time profile of the ion pulse. In result, when compared to the simple targets, the present class of four-layer targets is characterized by the same three driver parameters and by six (instead of four) target parameters. The two additional parameters are the inner and the outer radii of the intermediate low-Z absorber layer. Optimization has been performed over all the six target parameters, with the driver parameters fixed at some preassigned values. All calculations have been done with the three-temperature hydrodynamic code DEIRA, which accounts also for energy transport by fast alpha particles in the approximation of a separate diffusion equation for the alpha-particle energy density.

The main series of calculations was performed for the driver parameters $E_{in} = 6.12$ MJ, $P_{in} = 720$ TW ($t_{in} = 8.5$ ns), and $E_b = 10$ GeV per nucleus of ^{209}Bi . As the outcome of optimization, a target with the energy gain $G = 417$ has been found. The optimum values of the free target parameters (for the notation see Figure 2) are: $R = 4.912$ mm, $R_a = 4.822$ mm, $R_p = 4.512$ mm, $R_{DT} = 4.5$ mm, $R_c = 4.28$ mm, and $\rho_c = 3 \times 10^{-4}$ g/cm³. In this target the spark ignition of 12 mg of equimolar DT has been achieved. The hydrodynamic efficiency of the implosion turned out to be $\eta = 0.25$. At maximum compression $\langle \rho r \rangle_{DT} = 3.6$ g/cm². The radial convergence ratio is 20 for the fuel as a whole and 50 for the spark region.

Having performed the optimization for the same values of E_{in} and t_{in} but for $E_b = 20$ GeV, we could not reach the spark ignition, and the maximum energy gain was a meager $G = 120$.

Thus, we conclude that even in the class of single-shell targets with an intermediate low-Z absorber layer, irradiated by a non-profiled box-shaped ion pulse, close to the limiting energy gains of $G \gtrsim 400$ can be achieved. To raise the target gain even higher by elaborating its design is hardly possible because, in the most general case, $G = \eta G_c$, where the core gain G_c is limited by the value $G_c \lesssim 2000$ (for fuel masses $M_{DT} \leq 10$ mg)³, and there seems to be no realistic way to surpass the values $\eta = 0.25\text{--}0.3$ for the hydrodynamic efficiency².

4 SPHERICAL D₂ TARGETS

An attempt has also been undertaken to find a pure deuterium target with a maximum possible energy gain. As contrasted to DT targets, in pure deuterium the spark ignition configuration provides no advantage over the uniform one³, and the optimum parameters of the volume ignition $T_{DD} \simeq 2$ keV, $\rho_{DD} \gtrsim 2000$ g/cm³, $\langle \rho r \rangle_{DD} \gtrsim 20$ g/cm² correspond to a very low entropy of the compressed fuel. To

compress the D_2 fuel along the lowest possible adiabat, we have employed an ion pulse with the time profile

$$P_{in}(t) = \begin{cases} \frac{P_1}{(1 - t/t_0)^n}, & 0 < t \leq t_1, \\ P_2 \equiv \frac{P_1}{(1 - t_1/t_0)^n}, & t_1 < t < t_{in}. \end{cases} \quad (1)$$

For the fixed initial P_1 and final P_2 beam power values and the total input energy E_{in} , the pulse profile (1) has two free parameters: the pre-pulse duration t_1 and the exponent index n . The target structure is exactly as shown in Figure 2, with the only difference that DT is replaced by D_2 .

Optimization has been performed over the six target parameters and the two free parameters of the pulse profile, as given in Eq. (1) for the values of $E_{in} = 100$ MJ, $P_1 = 10$ TW, $P_2 = 10^4$ TW. For the energy of ^{209}Bi ions the value $E_b = 12.5$ GeV was chosen which produced the best results over the range $10 \text{ GeV} \leq E_b \leq 20 \text{ GeV}$. Calculations have been done with the three-temperature code DEIRA which accounts for the energy transport by 3.5–3.6 MeV alpha particles and by 3 MeV and 14 MeV protons in the framework of the diffusion approximation.

As a result, a target with the energy gain $G = 9.8$ has been found. Its principal parameters turned out to be $R = 6.492$ mm, $R_a = 6.352$ mm, $R_p = 6.042$ mm, $R_{DD} = 6.0$ mm, $R_c = 5.87$ mm, and $\rho_c = 3 \times 10^{-5}$ g/cm³. The optimum values of the prepulse parameters are $t_1 = 24$ ns, and $n = 3.5$; with those, the prepulse contains 15.5% of the total input energy $E_{in} = 100$ MJ. The hydrodynamic efficiency of this target turned out to be rather low, $\eta = 0.11$. The mass of D_2 fuel is $M_{DD} = 10.4$ mg. The fuel is compressed to $\langle \rho r \rangle_{DD} = 20$ g/cm², $\rho_{DD} = 1800$ g/cm³. The fuel convergence ratio is 50. Thus, even under rather severe requirements for the heavy ion driver (a tailored pulse with a peak power of $P_2 = 10^{16}$ W), we were unable to find a pure deuterium target with an energy gain $G > 10$.

5 NON-ONE-DIMENSIONAL DIRECTLY DRIVEN TARGETS

Since steering the beam of accelerated ions beyond the horizontal plane of accelerator would be a very difficult task, cylindrical rather than spherical symmetry of illumination by heavy ions appears much more natural and easy to achieve. To demonstrate how cylindrical symmetry of illumination can be reconciled with spherical implosion under the conditions of direct drive, we have performed numerical simulations of the following quasispherical DT target.

Consider an axially symmetric target with an overall structure close to that shown in Figure 2, illuminated by an axially symmetric beam of heavy ions, which propagate strictly along the cylindrical radii. The interior of the target is perfectly spherical, while the thickness of the outer tamping layer—made of lead—is adjusted so as to make all the ions stop at the spherically-symmetric Be/Au interface (or along the target axis within the Be layer). Calculations of this target have been performed with

a two-dimensional hydrodynamic code without thermal conductivity. The heating by the ion beam was simulated as a uniform specific energy release, 0.5 TW/mg in the Pb tamper and 1.5 TW/mg in the Be absorber. As earlier, the total energy of 6 MJ was injected within the 17-ns pulse. For all materials the ideal-gas equation of state was used. As a result, it was demonstrated that the ignition conditions $\langle \rho r \rangle_{DT} \gtrsim 3 \text{ g/cm}^2$, $T_{DT} \gtrsim 2 \text{ keV}$ can be reached in the DT fuel. Thus, two-dimensional hydrodynamic calculations (though in the framework of a rather simple physical model) show that departures from spherical symmetry in the illumination pattern by heavy ion beams can (at least, under certain conditions) be amended by means of pure hydrodynamic effects.

Another possible approach to exploit the cylindrical symmetry of illumination is to design a cylindrically-symmetric target. Hydrodynamic cumulation observed in cylindrical implosions is less effective than that in spherical case and, to facilitate the thermonuclear ignition, we propose to make use of a strong axial magnetic field ($B \simeq 10^8\text{--}10^9$ gauss at maximum compression), which can strongly reduce the electron thermal conductivity and the energy transport by charged products of nuclear reactions in radial direction. Then, the well-known ignition criterion $\langle \rho r \rangle \gtrsim \langle \rho r \rangle_0$ is modified to a purely hydrodynamic condition⁴

$$\langle (\rho \rho_p)^{1/2} r \rangle \gtrsim \langle \rho r \rangle_0, \quad (2)$$

where ρ is the fuel density, ρ_p the pusher (liner) density, and r the cylindrical radius of the central fuel region. For a constant pressure at the time of maximum compression, typical values of the pusher/fuel density ratio are $\rho_p/\rho \simeq 10$ and the traditional $\langle \rho r \rangle$ criterion is mitigated by approximately a factor of three. This provides an opportunity to utilize pure deuterium as the main component of the thermonuclear fuel in cylindrical targets.

A conceptual design of a magnetized cylindrical D_2 target with an initiating DT section is shown in Figure 3. The DT section is about 0.5 cm long. A 10% (by number of atoms) admixture of ^3He is added to the D_2 fuel in the main target section. Initially, D_2 fuel is assumed to be concentrated in the form of a solid cylindrical shell of radius $r_0 = 0.5 \text{ cm}$ and mass 10 mg/cm. Along its main section, the target is illuminated by a cylindrically-symmetric beam of ^{209}Bi ions with the energy $E_b = 25 \text{ GeV}$ and power $P_{in} = 140 \text{ TW/cm}$ over the time interval of $t_{in} = 100 \text{ ns}$. The initial specific entropy of the DT fuel and the beam parameters along the initiating section are supposed to be adjusted in such a way as, on the one hand, to synchronize the times of maximum compression in the DT and D_2 sections and, on the other hand, to ensure bootstrap heating and high ion temperatures in the DT part. Under such conditions, the total energy input into a 10-cm-long target will be $\simeq 150 \text{ MJ}$.

The performance of this target was simulated by combining several one-dimensional and 1.5-dimensional (with full z dependence and a single-zone approximation along the r coordinate) calculations. At maximum compression, the fuel reaches $\rho_{DD} \simeq 100 \text{ g/cm}^3$, $\langle \rho r \rangle_{DD} \simeq 0.5 \text{ g/cm}^2$. The convergence ratio over the cylindrical radius is $r_0/r_{\min} = 100$. Then, a thermonuclear flare develops in the DT section of the target and the ion temperature rises up to $\sim 100 \text{ keV}$. High pressure in DT initiates a self-sustained detonation wave propagating along the z -axis of the D_2

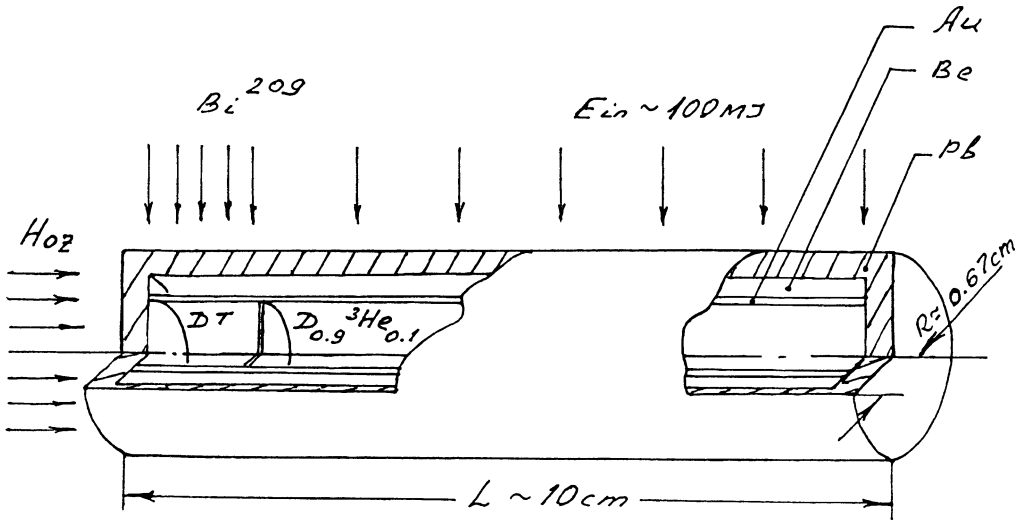


FIGURE 3 Schematic view of a cylindrical D_2 target with magnetic thermal insulation of the fuel.

channel, provided that 3.5–3.6 MeV alpha particles and 14-MeV protons are magnetically confined and deposit all their energy in the fuel region. For this a magnetic field of $\approx 10^9$ G in the compressed state (the initial field $\approx 10^5$ G) is needed. Two-dimensional hydrodynamic calculations, with the four principal nuclear reactions in D_2 fuel accounted for, have confirmed that under such conditions there develops a steady-state detonation wave in which about 10% of the $D_{0.9}{}^3\text{He}_{0.1}$ fuel is depleted. As a result, an energy gain of $G \approx 20$ is achieved, which exceeds the value $G = 10$ obtained in the course of optimization of spherical D_2 targets. Thus, cylindrical targets with magnetic thermal insulation of the fuel appear as a promising alternative under the conditions of realistic axially-symmetric illumination by heavy ion beams. Note that, as a $\sim 10\%$ initial admixture to the deuterium fuel, ${}^3\text{He}$ actually serves as a catalyst to the DD nuclear reaction cycle.

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