Numerical study of fast ignition of ablative imploded deuterium–tritium fusion capsules by ultra-intense proton beams

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Compression and ignition of deuterium–tritium fuel under conditions relevant to the scheme of fast ignition by laser generated proton beams [Roth et al., Phys. Rev. Lett. 86, 436 (2001)] are studied by numerical simulation. Compression of a fuel containing spherical capsule driven by a pulse of thermal radiation is studied by a one-dimensional radiation hydrodynamics code. Irradiation of the compressed fuel by an intense proton beam, generated by a target at distance \( d \) from the capsule center, and subsequent ignition and burn are simulated by a two-dimensional code. A robust capsule, absorbing 635 kJ of 210 eV (peak) thermal x rays, with fusion yield of almost 500 MJ, has been designed, which could allow for target gain of 200. On the other hand, for a reasonable proton spectrum the required proton beam energy \( E_{\text{ig}} \), exceeds 25 kJ (for \( d = 4 \) mm), even neglecting beam losses in the hohlraum and assuming that the beam can be focused on a spot with radius of 10 \( \mu \)m.

The effects of proton range lengthening due to the increasing plasma temperature and of beam temporal spread caused by velocity dispersion are discussed. Ways to reduce \( E_{\text{ig}} \) to about 10 kJ are discussed and analyzed by simulations. © 2002 American Institute of Physics.

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I. INTRODUCTION

In this paper, we study some aspects of the recently proposed scheme of inertial confinement fusion (ICF) fast ignition by laser accelerated proton beams.\(^1\) The fast ignition approach to ICF consists in first compressing the fuel to high density by a suitable driver and then creating the hot spot required for ignition by means of a second external pulse. When compared with the standard ICF scheme, relying on central ignition by hydrodynamic cumulation,\(^3,4\) fast ignition offers several potential advantages.\(^2,5–7\) Fast igniters are less sensitive to implosion asymmetries and instabilities, and may achieve higher energy gain at given driver energy, or achieve a given gain at smaller driver energy. On the other hand, a highly focused, ultra-intense ignition pulse is required to create the hot spot in the dense fuel in a time shorter than the relevant confinement time. Indeed, the fast ignition proposal\(^2\) just followed developments in short pulse lasers,\(^8\) indicating that laser pulses may achieve the parameters required for fast ignition. In the original scheme, the ignition hot spot is heated by relativistic electrons generated by ultra-intense laser–plasma interaction. This approach and related variants are currently investigated at several laboratories. The issues faced by the scheme concern the complex nonlinear relativistic plasma physics associated to generation and transport of the hot electrons. Overviews of relevant research and collection of recent papers can be found in Refs. 9–16.

Recently, following experimental evidence for the generation of beams of multi-MeV protons in the interaction of ultra-intense laser beams with solid targets,\(^17–22\) Roth et al.\(^1\) have proposed to use such laser-produced proton beams as fast ignition drivers. The advantage of protons over hot electrons would consist in their classical slowing down.

According to Roth et al., laser produced protons have a range appropriate to create a hot spot in deuterium–tritium (DT) fuel, can be transported for a distance of a few mm and focused to spots of 15 \( \mu \)m radius. The scheme they suggested then consists in a standard ICF hohlraum, where a capsule containing DT fuel is ablative compressed by thermal radiation, and a properly shaped proton source placed just outside the hohlraum (see Fig. 1). At a time close to maximum compression of the fusion fuel, a bundle of ultra-intense laser beams is focused on this second target, which emits a burst of protons, directed towards the compressed fuel. Using standard range computations and the results of Ref. 7 concerning particle beam requirements for fast ignition, Roth et al. estimated that 7–10 kJ of 15–23 MeV protons, reaching the fuel in a 15–20 ps pulse and focused onto a spot of 15 \( \mu \)m, are required to fast ignite the fuel compressed to a density of 400 g/cm\(^3\). (Energy, radius, and pulse duration scale\(^7\) with density as \( E_{\text{ig}} \propto \rho^{-1.85} \), \( r_b \propto \rho^{-1} \); \( \tau_p \propto \rho^{-0.85} \), respectively; for other studies on fast ignition requirements see Refs. 6, 23, and 24.) However, these results refer to an ideal particle beam (with range just fitted to the hot spot size and independent on temperature and density) interacting with a homogenous fuel sphere. In fact, since protons are produced with a wide energy spectrum,\(^17–21\) pulse power and length will be a function of both spectrum and distance between source and compressed fuel. Also, pro-
ton range is a function of both proton energy and plasma conditions.\textsuperscript{25,26} In addition, the compressed fuel will not be isochoric. A more complete analysis is therefore needed. A first step in this direction was taken in our work reported in Ref. 27. There, we showed that due to the range dependence on plasma temperature and power spread due to proton velocity dispersion, the minimum ignition energy (for a homogeneous fuel sphere) is larger than that estimated in Ref. 1. A good fit to results referring to a certain simple proton energy distribution is $E_{\text{ig}} = 90\left(\frac{d}{\text{mm}}\right)^{0.7}\left(\frac{\rho}{(100\text{ g/cm}^3)}\right)^{1.3}$ kJ.

This paper is motivated by the need for an improved and more detailed analysis of proton beams as ignition triggers. Here, we present numerical simulations of a fuel capsule first imploded by a radiation pulse and then ignited by a proton beam. To test the dependence on the proton energy distribution, we consider two different spectra; the choice is rather arbitrary, but suffices to get insight and understand trends. A few cases are analyzed in detail to show the influence of the various effects on the dynamics of ignition. Finally, we present results concerning alternative configurations of the compressed fuel that allow to place the proton source very close to the fuel. The analysis of these configurations reveals some aspects of the physics of conically guided targets, which have been proposed for fast ignition by electrons\textsuperscript{28–30} and by protons.\textsuperscript{27}

We study capsule implosion by the 1D multigroup radiation-hydrodynamic code SARA\textsuperscript{31} up to a time close to maximum fuel compression is attained; then we remap the hydrodynamic data onto the mesh of the 2D radiation-hydrodynamic code DUED (Ref. 32 and refs. therein), which simulates proton beam interaction, fuel ignition and burn. In the DUED code proton–plasma interaction is dealt with by the model by Basko,\textsuperscript{26} which applies binary collision theory\textsuperscript{33} to a plasma of arbitrary ionization and degeneration, and also accounts (in a simple way) for ion correlation. Such a treatment extends that by Mehlihorn,\textsuperscript{25} widely employed in ion-beam driven inertial fusion simulations. It is worth mentioning that degeneracy effects are also included in the equation-of-state and radiation opacities employed by the codes SARA and DUED.

The remainder of this paper is organized as follows. In Sec. II, we discuss target configuration, the 1D design of a radiation driven capsule suitable for fast ignition, and modeling of the proton beam. In Sec. III, we present results of 2D numerical simulations concerning the stages of ignition and burn. We discuss the results of a parametric study of the ignition requirements, as well as a detailed analysis of proton–fuel interaction. In Sec. IV, we present results of simulations relevant to targets (such as conically guided spherical capsules) allowing for direct heating of the central fuel region and a shorter distance $d$. Finally, some conclusions are drawn in Sec. V.

II. SIMULATED TARGET

We refer to target concepts as proposed by Roth et al.\textsuperscript{1} There, the x rays generated within a hohlraum, first compresses a fuel-containing capsule. At a time close to maximum fuel compression, an ultra-high power laser irradiates the target placed outside the hohlraum at distance $d$ from the capsule center. This target releases a collimated proton beam directed towards the compressed fuel (see Fig. 1). Outstanding issues of the scheme concern proton beam generation, transport, and dynamics. These are currently being studied experimentally,\textsuperscript{13,16–22} theoretically\textsuperscript{34} and by means of numerical simulations.\textsuperscript{34–36} We are aware of these issues; in particular, nonlinear processes (not included in our stopping model) can hinder proper focusing or could even degrade beam plasma coupling, thus reducing the efficiency of the scheme. However, we take a complementary point of view. Namely, we assume that a suitably collimated proton beam impinges on the compressed fuel and is stopped collisionally. We then study the requirements this beam has to fulfill in order to fast ignite a fusion fuel by a proton beam, and possible ways to make them less demanding. Furthermore, we do not perform a fully integrated target study, but restrict our attention to the stages of fuel implosion, ignition, and burn. Therefore, we study the implosion of a radiatively driven capsule, and the proton beam driven ignition of the compressed fuel.

A. Fusion capsule implosion and fuel compression

Since in fast ignition the hot spot is created by an external source, the only purpose of the implosion process is fuel compression. In addition to relaxing the requirements on implosion symmetry, lower implosion velocities are required and higher gains can be achieved\textsuperscript{2,6,7,37} because ignition occurs in a homogeneous (or isochoric) fuel rather than an isobaric one. Notice that lower implosion velocities imply increased robustness to Rayleigh–Taylor instability.\textsuperscript{2,4} However, to fully take advantage of this option, one has to perform specific capsule design. Here, we study a design of a reactor-size capsule, containing $3.5$ mg of DT fuel, with potential for high gain. The goal of the design is the achievement of the needed compression with very low entropy production.

The basic capsule design is shown in Fig. 2. The radius of the capsule is fixed by the radius of the hohlraum, which should be less than $4$ mm in order to control the time spread of the proton pulse (see Sec. II B). Beryllium has been se-
shocks arrive equally spaced in time at the inner surface of the DT layer [see Fig. 2(b)]. The radial profiles of temperature and density of the imploded fuel at stagnation are shown in Fig. 3. Note that although the central region is not as hot as in a standard capsule for central ignition, the density profile is still not uniform at the time of the maximum value of the confinement parameter \( \rho r \), because at this time the rebound shock has propagated through half the DT fuel mass. The desired nearly isochoric configuration is instead attained when the shock has just passed through the whole fuel. At this time, the density confinement parameter \( \rho r \) is reduced to 80% of its peak value and the density to 50% of the peak. The parameters of the reference capsule considered in the following are shown in Table I. For the sake of a comparison, we also show the parameters of the centrally ignited capsule described in Ref. 42, which contains nearly the same mass of DT and is compressed by a radiation pulse with slightly higher peak temperature.

Since protons deposit most of their energy in the shell behind the rebound shock, the capsule has been designed to achieve a sufficiently high \( \rho r \) in the shell to stop multi MeV protons. Taking into account the range lengthening effect at temperatures of keV (see Fig. 4), the \( \rho r \) of the shell has been taken equal to 2.4 g/cm\(^2\) at time of peak \( \rho r \) of the fuel (later on it increases up to 2.7 g/cm\(^2\)). In addition, high densities in the shell are also beneficial from the viewpoint of the ignition energy. Designs with lower densities (\( \rho_{\text{peak}} \))
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TABLE II. Proton energy distributions.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>“E”</th>
<th>“M”</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dn/d\epsilon$</td>
<td>$dn/d\epsilon \propto e^{-\epsilon T_p}$</td>
<td>$dn/d\epsilon \propto \epsilon^{3/2} e^{-\epsilon T_p}$</td>
</tr>
<tr>
<td>Beam power (at distance $d$)</td>
<td>$P_{bd}(t)=\frac{E}{\tau} \frac{\tau}{\tau} e^{-\epsilon(t)}$</td>
<td>$P_{bd}(t)=\frac{8}{3} \frac{E}{\tau} \frac{\tau}{\tau} e^{-\epsilon(t)}$</td>
</tr>
<tr>
<td>Peak power</td>
<td>$P_{peak}=1.6E/\tau$</td>
<td>$P_{mpeak}=2E/\tau$</td>
</tr>
<tr>
<td>Time of peak power, $t_{peak}$</td>
<td>$T_{p}=\sqrt{\frac{E}{\epsilon}}$</td>
<td>$\langle S/2 \rangle T_{p}$</td>
</tr>
<tr>
<td>Average proton kinetic energy</td>
<td>$\epsilon(t_{peak})=(\frac{5}{2})T_{p}$</td>
<td>$\epsilon(t_{peak})=3T_{p}$</td>
</tr>
<tr>
<td>Proton kinetic energy at $t=t_{peak}$</td>
<td>$\epsilon(t_{peak})=(\frac{5}{2})T_{p}$</td>
<td>$\epsilon(t_{peak})=3T_{p}$</td>
</tr>
</tbody>
</table>

About the time of maximum compression of the fuel, ultra-intense laser beams irradiate the target placed outside the hohlraum and generate the proton beam required for fast ignition. The stage of beam–fuel interaction is intrinsically nonsymmetrical and therefore requires 2D or 3D simulations. We study this process by the 2D Lagrangian code DUED. To such a purpose, we map the 1D hydrodynamics quantities evaluated by the SARA code onto the DUED mesh, and then let DUED evolve two-dimensionally.

B. Proton beam model

As anticipated, proton beam properties are crucial for the scheme, but present knowledge and understanding does not allow us to make realistic extrapolations to the energies and currents required for fast ignition. Therefore, we take a simple model, which may serve to understand requirements and issues.

We assume that protons are emitted in a burst of negligible duration by a source located at distance $d$ from the center of the compressed fuel. This assumption is justified by the fact that mechanisms generating fast protons only act for a few ps, while proton velocity dispersion results in a pulse duration of tens of ps at distance of a few mm from the source (see below). Any assumption concerning beam transport and focusing is highly arbitrary. Experiments\textsuperscript{16–22} give some indications on source divergence; on the other hand simulations\textsuperscript{34} indicate that it could be possible to focus the protons by using appropriately shaped targets. Here, for simplicity, we assume that fast protons form a cylindrical beam with uniform radial intensity profile. For the beam radius $r_b$ we take $r_b=15/\left(\rho_s/(400\ \text{g/cm}^3)\right)$. According to Ref. 7, this value minimizes the energy required to ignite a homogeneous fuel sphere. Therefore, we choose $r_b=10\ \mu\text{m}$ for the reference capsule discussed above, with peak density $\rho_s=625\ \text{g/cm}^3$ at the time of interaction with the beam.

Next, we have to model proton energy spectrum. Different experiments show somewhat different distributions, both concerning energy and angular dependence. In general, however, one observes that an important portion of the spectrum can be fitted by an exponential distribution. In some cases the entire spectrum is well fitted by a two-temperature distribution,\textsuperscript{35} while in other cases some peaks or plateau appear.\textsuperscript{18} In addition, experiments indicate the existence of a high energy cut-off. Given the obvious difficulties of extrapolation, we have chosen to take simple model distributions (see Table II), which should however allow to get insight in the relevant physics. In particular, we have chosen a simple exponential distribution (labeled as “E”), and the additional one labeled as “M” in Table II.

As shown by the table both distributions are characterized by a temperature $T_{p}$ and a time scale $\tau=\left[\left(m_{p}d^{2}/(2T_{p})\right)^{1/2}\right]/72\ d\ (\text{mm})/[T_{p}\ (\text{MeV})]^{1/2}$ ps. We see that the short pulse duration (less than 20 ps for DT density of 300 g/cm$^3$) required for minimizing fast ignition energy\textsuperscript{2,6,7} can only be achieved by small distance $d$ and/or high proton temperatures $T_{p}$.

On the other hand, proton temperatures cannot be taken arbitrarily large, because corresponding proton ranges would be unfit to hot-spot heating. Earlier studies,\textsuperscript{7} assuming constant stopping power, indicate that using heating particles with range in the interval 0.6–1.2 g/cm$^2$, minimizes fast ignition requirements. In fact, stopping powers for a given projectile-target pair depend on particle energy and target temperature (and, to a lesser extent, on target density). In Fig. 4 we show the ranges of protons with different initial energy in compressed DT plasma. We see that in a relatively cold plasma, with $T<1 \text{ keV}$, optimal proton energies are 10–25 MeV. However, as the plasma heats to the temperatures required for ignition the range lengthens considerably. At $T=5 \text{ keV}$, the most suited proton energies are 3–10 MeV. This indicates a clear preference for relatively low proton temperatures, in contrast with the previous requirement concerning pulse length. The optimal proton temperature will, therefore, result from a compromise.

Concerning the difference between the two distributions, we observe that for a given proton temperature $T_{p}$, total proton energy $E$ and distance $d$, the peak power $P_{mpeak}$ is higher than $P_{epeak}$ and is reached at earlier time.

400 g/cm$^3$ would lead to higher gain but require excessive ignition energy (>70 kJ), while designs with higher densities would lead to unacceptably high compression works. Our capsule may be a reasonable compromise between target performance and short pulse ignition energy.

It is worth noting that the results shown in Table I agree with those of a recent study by Slutz and Hermann.\textsuperscript{30} For instance, the scaling formulas proposed in this reference give for our design a stagnation density $\rho_s=24A_R^{0.7}\ T_{peak}/(100 \text{ eV})^{2.8}=576\ \text{g/cm}^3$, and a peak mean density $\langle \rho \rangle=0.34\rho_{peak}A_R^{0.25}=315\ \text{g/cm}^3$, where $A_R$ is the initial aspect ratio of the capsule and $T_{peak}$ the peak radiation temperature. Simulations give $\rho_s=550\ \text{g/cm}^3$ at the time of peak $\rho r$ and $\langle \rho \rangle=320\ \text{g/cm}^3$.

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III. PROTON BEAM DRIVEN IGNITION OF THE COMPRESSED FUEL

We have performed a parametric study to compute the proton beam energy needed for ignition and burn propagation, as a function of the temperature $T_p$, and of the distance $d$ between source and compressed fuel. We have considered the fuel assembly generated by the implosion of the capsule described in Sec. II and, in addition, a uniformly compressed fuel with $\rho = 400 \text{ g/cm}^3$. This ideal case approximates the density profiles of the considered capsule at a time about 370 ps after the time of maximum density profile, when the density profile is nearly isochoric (see Fig. 3). In Fig. 5 we show the ignition energies $E_{ig}$ obtained from 2D simulations for both the realistic capsule and the homogeneous fuel, for both proton velocity distributions ("$E$" and "$M$"). For given fuel assembly and distance, the ignition energy is minimum for an optimal temperature $T_p$ of 3 to 4 MeV.

From Fig. 5 we see that for the reference capsule the minimum ignition energy $E_{ig} = 15 \text{ kJ}$ for $d = 1 \text{ mm}$ (incompatible with the hohlraum concept of Fig. 1), while $E_{ig} = 26 \text{ kJ}$ for $d = 4 \text{ mm}$. The growth of $E_{ig}$ with $d$ is the result of power spread due to velocity dispersion ($P_{peak} \propto E/T_p \propto \rho d/T_p^{1/2}$). Ignition energies for the homogeneous DT sphere with $\rho = 400 \text{ g/cm}^3$ follow the same trends, but are somewhat larger than for the implored capsule, due to the smaller density. This is in qualitative agreement with the scaling $E_{ig} \propto 1/\rho^{1.3}$ found for homogeneous fuels.27

Concerning the two considered proton energy distributions, simulations show the same trends. The ignition energy for the exponential distribution is somewhat higher than for the second distribution. This is because the effective pulse duration is shorter for the distribution "$M$" and because power $P_{T}(t)$ is larger than $P_{E}(t)$ for the protons with kinetic energy $E > (9 \pi/16) T_p$. This energy range includes the protons with range most suited for hot spot heating, and therefore contributing most to the ignition process.

We now analyze in detail a reference case (hereafter referred to as case A), in order to get insight in the processes of beam heating and ignition, and also to get hints on possible ways to relax ignition requirements. We refer to the compressed fuel generated by the implosion of the reference capsule of Sec. II, irradiated by a proton beam with energy distribution "$M$," $T_p = 3 \text{ MeV}$, and total energy $E_{ig} = 26 \text{ kJ}$, emitted by a source located at $d = 4 \text{ mm}$ from the compressed fuel.

Ignition and propagation of thermonuclear burn wave are illustrated by Fig. 6, showing a sequence of 2D temperature and density maps at selected times. Ignition occurs in the nearly cylindrical volume of radius $r_b$ and length comparable to the proton range. After ignition, around $t = 105 \text{ ps}$, a burn wave propagates nearly spherically to the unperturbed fuel. The wave moves faster in the central region where the density is lower ($\sim 200 \text{ g/cm}^3$), and slower in the denser shell. At about 155 ps, the burn wave reaches the shell at left side, so that a large part of the fuel volume is burning.

This fusion capsule releases a total fusion energy $E_{fus} = 488 \text{ MJ}$. The overall target energy gain $G$ (fusion energy to driver energy) one can expect from the whole hohlraum target can roughly be estimated as $G = E_{fus} / E_w \eta_h + E_{ig} / \eta_{FL}$, where $\eta_h$ is the hohlraum to capsule coupling efficiency, $E_w$ the energy needed for the compression of the capsule, $\eta_{FL}$ the efficiency of proton generation and transport, and $E_{ig}$ the proton beam energy. In our case, $E_w = 635 \text{ kJ}$, $E_{ig} = 26 \text{ kJ}$, and assuming $\eta_h = 0.3$ (as in Ref. 43) and $\eta_{FL} = 0.12$ (as reported in Ref. 17), we get $G = 209$. con-
firming the potential of the scheme for energy production. Notice that, reduction of the efficiency of proton generation would not reduce the gain substantially, e.g., for $\eta_{FI} = 0.06$ and $\eta_{FI} = 0.03$, we would have $G = 191$ and $G = 164$, respectively. On the other hand, the laser energy required for generating the ultra-intense proton pulse scales as $1/\eta_{FI}$. With the optimistic value $\eta_{FI} = 0.12\%$ we need a 220 kJ pulse. Any decrease in generation efficiency or any degradation of coupling, due, e.g., to plasma instabilities affecting transport and focusing, would lead to larger values.

In Fig. 7 we show the time dependence of the delivered proton beam power, of the fusion power, and of the kinetic energy of the protons hitting the fuel. In the same figure, we also show the proton ranges ($R_1$, $R_2$, $R_3$) evaluated in the three following different situations. The curve $R_1(t)$ refers to the proton range for the reference simulations. Curve $R_3(t)$ refers to the same case, but with fusion reactions artificially switched off; curve $R_2(t)$ refers to a zero-power beam, which does not affect plasma dynamics. (Since paths of protons with different radial coordinate, relative to the beam axis, differ slightly from each other, the three curves represent averaged values at each time.) At the beginning of the interaction we observe a substantial decrease of the range, due to the decreasing energy of the protons arriving at the fuel. For instance, in the interval 45 ps < $t$ < 55 ps proton energy decreases from 40 to 27 MeV, and the range decreases from 2.6 g/cm$^2$ to about 1 g/cm$^2$. At this time the plasma is still relatively cold and one cannot observe any difference between the three range curves. Around time $t = 55$ ps, when the beam power grows up to a few tens of TW, the curve $R_3$ continues to decrease monotonically as the proton energy decreases in time and plasma conditions do not change appreciably, while the ranges $R_1$ and $R_2$ decrease more smoothly up to time 63 ps and then grow again, as the range lengthening effect due to plasma heating dominates over shortening due to the decrease of the proton energy. About time $t = 83$ ps curves $R_1$ and $R_2$ start to behave differently from each other. At this time, indeed, energy deposition by fusion products causes bootstrap heating and ignition. The range $R_1$ (corresponding to the case accounting for fusion reactions and energy deposition) continues to grow, while $R_2$ decreases again.

Analyzing more in detail the curve $R_1(t)$, we see that the range $R_1$ takes a minimum of about 0.9 g/cm$^2$, while the proton power still increases, but ignition has not yet occurred. Both the rising power and range reduction allow for a higher specific energy deposition and for a fast increase of the temperature of the heated region. Subsequently, when range lengthening takes place, the protons penetrate deeply into the plasma, heating progressively additional DT fuel mass. After ignition, as the thermonuclear burn wave is propagating away from the interaction area, the proton range stabilizes about 1.4 g/cm$^2$.

It is worth observing that, when a fusion fuel is heated by a proton beam with a velocity distribution such as considered in this paper, range lengthening of the protons as the plasma heats has the following positive effect. The first protons (with higher kinetic energy) heat preferentially a certain region of plasma around the end of their range. The following less energetic protons have (at given plasma temperature) a shorter range, but they impinge on a already hot plasma and their range lengths. These allow them to penetrate the plasma and to deposit their energy in the same region heated by the more energetic protons. Without this effect, the energy of such protons would be deposited in the corona and in the outer region of the fuel and would not contribute to the formation of the ignition hot spot.

From the proton range curve $R_1$ of Fig. 7 we infer that large part of the proton energy is deposited into the fuel region mass contained between 0.9 and 1.4 g/cm$^2$. This observation has led us to perform a few simulations considering only protons with energy included in the interval corresponding to proton ranges in the interval $0.9 < R < 1.4$ g/cm$^2$. We have, therefore, performed a simulation (referred as case B in Fig. 8) employing the reference beam, but only considering protons with kinetic energies between 7 and 19 MeV. The two energy limits correspond to the protons hitting the fuel between 65 and 105 ps (see the shadowed area in Fig. 7). In this case (B) the total energy carried by protons is only 10.5 kJ, which is only 40% of the energy (26 kJ) of the full spectrum. We find that ignition and burn occur just as in case A. Figure 8 also shows analogous curves for a third case.
electron heating of a compressed conically shaped target has a larger (same reference parameters as above, the ignition energy is considered above for the protons using Li ions). In particular, we have performed a few simulations using beams of heavier ions. We have also considered the possibility to use beams of heavier ions. In particular, we have performed a few simulations using Li ions (and the same velocity distributions as considered above for the protons). We found that, for the same reference parameters as above, the ignition energy is larger ($E_{\text{ign}} > 50$ kJ) than that needed by using a proton beam. This is due to the fact that higher particle energies are required to penetrate a given $pr$, which demands for higher beam temperature. Nevertheless, the large fraction of energy carried out by the lower energy ions does not contribute to heating the hot spot required for ignition.

IV. ALTERNATIVE FUEL GEOMETRY

As we have seen in Sec. III, the ignition energy that has to be delivered by the proton beam grows with the distance $d$ between source and dense fuel. As a mean to reduce such a distance one could use conically guided spherical targets, originally proposed for fast ignition by electrons. After the first proposal, 2D simulations have been carried out. Hot electron heating of a compressed conically shaped target has been demonstrated in a recent experiment. No study has so far been performed in the context of proton beam driven fast ignition. Here, we present the first preliminary 2D simulations.

Two quite different conical guiding systems have been suggested, characterized by the substantially different value of the angle $\beta$ defining the spherical sector filled by the fuel target (see Fig. 10). In one concept, $\beta < \pi/2$. This scheme tries to merge the positive effect of convergence to the simplicity of one sided-irradiation. In addition, it allows for easy access to the compressed fuel, since fast ignitor particle beams do not have to cross the corona. In the second concept, instead, $\beta > \pi/2$; ideally one would like to subtract from a sphere the smallest cone still allowing for delivering fast particles at the center. The main issue for both schemes is fuel compression, which requires both suitable irradiation geometry and limitation of boundary effects close to the cone surface. It appears more critical for targets with small $\beta$.

We have addressed this issue, but assume that the desired implosion has been achieved and study the stages of ignition and burn. In particular, we want (i) to check the expected reduction of the ignition energy due to the small distance between source and fuel, and (ii) to study how the departure from a full sphere affects burn efficiency. This last problem is certainly more significant for capsules with small values of $\beta$. For this reason, and for code limitations, we have limited our study to $\beta \leq \pi/2$.

To simulate this target concept we then assume that conical guiding does not affect significantly implosion dynamics, so that the status of the compressed fuel can be taken from the 1D simulation presented in Sec. II. This assumption is supported by the experimental results of Kodama et al. and also by the simulations of Hatchett et al. In particular, Kodama et al. pointed out that the insertion of the cone reduces the compressed density by about 20%–30% compared with full spherical implosion. Thus, we proceed here similarly to Sec. III. First, the 1D plasma profiles are remapped, as before, onto the whole 2D mesh referring to the full sphere. However, in this case, the cell meshes in the region outside the simulated cone are filled with a fictitious material, which does not interact with the fast protons and does not undergo fusion reactions. It only acts as an inertial tamper for the plasma inside the cone. In this way, we simulated the conical guided sector of a capsule in a simplified fashion, but we believe this should not significantly affect the evaluation of the igniting energy.
As an example of a simulation, in Fig. 11 we show the evolution of a compressed fuel hemisphere (with initial radial profiles as in the reference cases of the previous section), hit by a proton beam (with the same proton energy distribution as in case A of the previous section) coming from a source located at the distance \( d = 500 \mu m \) from the center. It can be seen that ignition occurs in the inner part of the shell, and is followed by burn propagation through the compressed shell. A strong shock moving in front of the wave is also observed.

Because of the reduced time-of-flight of the protons, the duration of the power pulse is favorable shortened from the 70 ps (full width at half maximum (FWHM)) of the reference case A of the previous section, (with \( d = 4 \) mm) to about 8 ps in this case. A second advantage follows from the easier access to the region of highest plasma density. The beam energy for ignition turns out to be \( 12-14 \) kJ for beams with access to the region of highest plasma density. The beam in this case. A second advantage follows from the easier evolutionary behavior of the power pulse duration due to velocity dispersion is now comparable with the presumable duration of the proton beam emission. Thermonuclear burn of the fuel releases 246 MJ, corresponding to about 50% of the yield of the corresponding spherical capsule. This shows that the burn efficiency (fractional burn) is practically the same as for the spherical capsule.

Let us now study the dependence of the burn fraction and of the target gain on the cone aperture \( \beta \). Let \( E_w/\eta_b \) be the energy needed to compress the whole spherical capsule and \( F_{V}(\beta)/[1-\cos(\beta)]/2 \) the volume of the conical shell relative to the spherical one. If we assume that the efficiency \( \eta_b \) is independent of \( \beta \), we can write the target gain \( G(\beta) \) as

\[
G(\beta) = \frac{E_{\text{fuel}}(\beta)}{\eta_b} \left[ F_{V}(\beta) E_w/\eta_b + E_{\text{ig}}/\eta_{F\text{I}} \right] F_{V}(\beta)/E_w/\eta_b \eta_{F\text{I}}.
\]

(1)

where \( E_{\text{fuel}}(\beta) = 340 m_{\text{DT}} \phi(\beta) F_{V}(\beta) \) MJ is the fusion energy, \( \phi(\beta) \) is the DT fractional burn-up and \( m_{\text{DT}} \) is the fuel mass of the spherical capsule in mg. As shown in Sec. IV, the yield of the spherical capsule is \( E_{\text{fuel}}(\beta = \pi) = 488 \) MJ. Taking \( E_w = 635 \) kJ, \( E_{\text{ig}} = 12 \) kJ (i.e., assuming a very small source-fuel distance), \( \eta_b = 0.3 \) and \( \eta_{F\text{I}} = 0.12 \) we estimate the maximum gain \( G_{\text{max}} = 220 \).

Since we expect that \( \phi(\beta) \) grows with \( \beta \), it follows that also \( G \) should monotonically increase with the angle \( \beta \) to reach its maximum value \( G(\pi) \) for \( \beta = \pi \). Under the assumption, the accuracy of which will be verified later, that \( \phi(\beta) \) is independent of \( \beta \) and equal to the value it takes for a full sphere, \( \phi(\beta = \pi) \), we get

\[
G(\beta)/G(\pi) = \frac{E_w/\eta_b + E_{\text{ig}}/\eta_{F\text{I}}}{[F_{V}(\pi) E_w/\eta_b + E_{\text{ig}}/\eta_{F\text{I}}]}.
\]

(2)

The accuracy of Eq. (2) has been checked by 2D simulations. Four simulations have been performed considering different conical angles \( \beta \), namely \( \beta = \pi/6, \pi/4, \pi/3 \), and \( \pi/2 \). These simulations provide the thermonuclear power and energy represented in Fig. 12 as function of time. Accordingly, the gain ratios \( G(\beta)/G_{\text{max}} \) are: 53%, 68%, 78%, and 96% for \( \beta = \pi/6, \pi/4, \pi/3 \), and \( \pi/2 \), respectively. Such values qualitatively agree with those given by Eq. (2) (61%, 79%, 88%, 96%, respectively), with the simulated data giving smaller gain ratios than Eq. (2) for small angles \( \beta \). This is due to the assumption of the constant fractional burn-up \( \phi(\beta) \) which, in turn, depends on the confinement time and it is thus expected to decrease with \( \beta \). Our results show that a hemispherical capsule \( (\beta = \pi/2) \) has a gain as high as 96% of that of the whole spherical capsule. (Actually, since the full sphere requires a larger distance \( d \), and hence higher ignition energy \( E_{\text{ig}} \), the gain of the hemispherical capsule would be even larger than that of the spherical one.) Concerning the cases with small values of \( \beta \), it is worth noting that they would allow to achieve substantial gain at smaller values of the total invested energy.

Of course, the actual viability of conically guided targets rests on the possibility of achieving the same compressions as in the spherical cases, and in limiting undesired effects associated with the cone boundaries. These topics deserve further numerical and experimental studies.

V. CONCLUSIONS

We have addressed some issues concerning the inertial confinement fusion scheme of fast ignition by proton beams generated by ultrahigh intensity lasers. In particular, we have
first studied the generation of a suitably compressed plasma configuration, and then the stages of proton beam driven ignition and burn. Concerning fuel compression, we have shown that in order to efficiently use the invested energy, it is necessary to employ properly shaped thermal x-ray drive pulses, with a pre-pulse substantially longer than in the case of standard capsules for central ignition. Consequences on the design of hohlraum targets have to be carefully evaluated.

Concerning beam driven ignition, our simulations rely on quite rough and simple assumptions concerning proton distribution, transport, focusing, etc. Furthermore, we completely neglected the interaction of the proton beam with the hohlraum environment. However, we believe our simulations still allow to get insight into the physics of ignition and to evaluate the parameters controlling the required beam energy. We have determined the minimum ignition energy as a function of the proton temperature and of the distance between source and fuel, for two different proton velocity spectra and two compressed fuel configurations. The required energy is larger than estimated by assuming monoenergetic beams, and is minimized if the proton temperature is larger than estimated by assuming monoenergetic transport and two compressed fuel configurations. The required energy could be reduced to about 10 kJ if one could completely neglect the interaction of the proton beam with the hohlraum and by range lengthening at high plasma temperature. A peculiar feature is observed in typical cases studied in this paper. As the plasma temperature rises to a few keV, due to the interaction with the initial portion on the proton pulse, proton range lengthening takes place. This effect compensates the reduction of proton kinetic energy allowing for a nearly constant range, and therefore, deposition in the same plasma region. We have shown that only a fraction of the whole proton distribution (including the protons with appropriate range and reaching the fuel in a short enough pulse) is really efficient to get ignition. We have then shown that the ignition energy could be reduced to about 10 kJ if one could control the proton spectrum.

A perhaps more realistic way to relax the ignition requirements consists in reducing the distance $d$ between proton source and compressed fuel, so as to reduce pulse duration and hence increase pulse power. This requires alternative target concepts. Here, we have presented simulations of the ignition of a sector of a sphere, which are relevant to conically guided targets. Simulations confirm that ignition energy can be substantially reduced ($E_{ig} = 12$ kJ at $T_p = 5$ MeV, $d = 500 \mu$m vs $E_{ig} = 26$ kJ at $T_p = 3$ MeV, $d = 4$ mm), and that the gain would not be degraded. For a half sphere the gain would be practically the same as for the whole spherical capsule (with only half drive energy being required). Therefore, we feel that the scheme deserves further studies addressing capsule irradiation and compression hydrodynamics.

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