

Fast ignition driven by quasi-monoenergetic ions: Optimal ion type and reduction of ignition energies with an ion beam array

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Abstract

Fast ignition of inertial fusion targets driven by quasi-monoenergetic ion beams is investigated by means of numerical simulations. Light and intermediate ions such as lithium, carbon, aluminum and vanadium have been considered. Simulations show that the minimum ignition energies of an ideal configuration of compressed Deuterium-Tritium are almost independent on the ion atomic number. However, they are obtained for increasing ion energies, which scale, approximately, as Z^2 , where Z is the ion atomic number. Assuming that the ion beam can be focused into $10\ \mu\text{m}$ spots, a new irradiation scheme is proposed to reduce the ignition energies. The combination of intermediate Z ions, such as 5.5 GeV vanadium, and the new irradiation scheme allows a reduction of the number of ions required for ignition by, roughly, three orders of magnitude when compared with the standard proton fast ignition scheme.

Keywords: Inertial Fusion Energy; Ion fast ignition; Laser-driven ion beams

1. INTRODUCTION

Fast ignition (FI) by laser-driven ion beams has been proposed (Tabak & Callahan-Miller, 1998; Roth *et al.*, 2001; 2009) as an alternative to the standard electron fast ignition scheme (Tabak *et al.*, 1994; Robinson *et al.*, 2014). This last scheme is limited by the high electron divergences and kinetic energies observed in experiments (Green *et al.*, 2008) and PIC simulations (Debayle *et al.*, 2010; Kemp & Divol, 2012). In addition, it is very sensitive to the energy level of the laser ASE (amplified spontaneous emission) prepulses (Baton *et al.*, 2008; Shiraga *et al.*, 2011). On the contrary, ion fast ignition (IFI) offers the advantages of a well known and well behaved ion-plasma interaction, a much more localized energy deposition and a stiffer ion transport with the possibility of beam focusing. A review of the IFI current status can be found in Fernández *et al.* (2014).

Recently, quasi-monoenergetic ion beams have been proposed for IFI (Fernández *et al.*, 2009). These ions can be generated by either laser-breakout afterburner (BOA) (Fernández

et al., 2009; Yin *et al.*, 2007; 2011a; 2011b, Hegelich *et al.*, 2013; Jung *et al.*, 2013), radiation pressure acceleration (RPA) (Macchi *et al.*, 2005; Robinson *et al.*, 2008) or ion solitary wave acceleration (ISWA) (Yin *et al.*, 2011c; Jung *et al.*, 2011) schemes, which use very thin foils, tens or hundreds nanometers in thickness, illuminated by sub-picosecond laser pulses. In addition, Weng *et al.* (2014) have proposed an *in-situ* hole boring IFI scheme to generate quasi-monoenergetic ions in overdense plasmas. Quasi-monoenergetic ions have several advantages over ions with Maxwellian energy distributions such as their better coupling with compressed fuel (Honrubia *et al.*, 2009) and the possibility to place the ion source far from the fuel without using re-entrant cones (Fernández *et al.*, 2009). The progress of IFI driven by quasi-monoenergetic ions has been summarized by Hegelich *et al.* (2011), where it is pointed out the experimental demonstration of the required (1) particle energies (400–500 MeV), (2) energy spreads (10–20%) and (3) conversion efficiencies (>10%). The chances over the forthcoming years to achieve experimentally all these simultaneously are high, very likely in new laser facilities. The focusing of ion beams to small spots (<30 μm) still awaits experimental confirmation.

It is relevant here to recall the substantial progress on proton focusing in cone targets reported recently by Bartal *et al.* (2012). It is based on the setting up of an electron sheath at the cone walls, which avoids the expansion of co-moving electrons and, thus, contributes to proton beam focusing. The spot size obtained in the experiments carried out by Bartal *et al.* (2012) suggests that it may be possible to focus protons onto the spots required for IFI. The cone wall focusing mechanism may reduce substantially the laser-to-proton conversion efficiency and the ion energy for the long pulses required in IFI. This can be mitigated by special designs of cone walls including insulator materials in order to reduce the electron flow between target and cone (Qiao *et al.*, 2013).

Here, we report on using heavier quasi-monoenergetic ions and propose an improved target irradiation scheme in order to minimize the ignition beam requirements and the number of ions to be accelerated. This may be critical for the successful demonstration of IFI in future high-power laser facilities such as HiPER (Dunne, 2006).

Full numerical modeling of the IFI scheme, from beam generation to fuel ignition, is not possible with the existing computer resources because it requires the integration of physical processes with very different spatial and temporal scales. Here, we use a simplified model that assumes a rather ideal initial ion distribution function and analyze the ion energy deposition and fuel ignition in an ideal IFI scenario with a precompressed fusion capsule.

This paper is organized as follows. After a short presentation of the computational model, the ignition energies of collimated beams of different ion species impinging on a pre-compressed DT target are presented as a function of the ion energy. Thus, we can show what is the optimal ion species for different ion acceleration conditions. Next, a new target irradiation scheme with an array of focused beams is proposed. This scheme reduces substantially the ignition energies, provided that ion beams can be focused into 10 μm diameter spots. The sensitivity of the ignition energies to the ion focal spot size is analyzed. Finally, conclusions and future work are briefly outlined.

2. SIMULATION MODEL

We assume cylindrical ion beams impinging on an ideal configuration of compressed DT fuel with the super-Gaussian density distribution $\rho(r) = \rho_{peak} \exp[-\log_2(r/R)^4]$, where r is the distance to the center, $\rho_{peak} = 500 \text{ g/cm}^3$, $R = 82 \mu\text{m}$ and the areal density is $\rho R = 2 \text{ g/cm}^2$. Two configurations of the ion beams are considered in this work: perfectly collimated (constant flux within its cross section) and focused ion beams, that are studied in Sections 3 and 4, respectively (Honrubia *et al.*, 2013). The simulation box used for perfectly collimated beams is shown in Figure 1. Ions come from the left and propagate toward the dense core through a low density plasma at 10 g/cm^3 . In the particular case shown in Figure 1 of quasi-monoenergetic ions sited

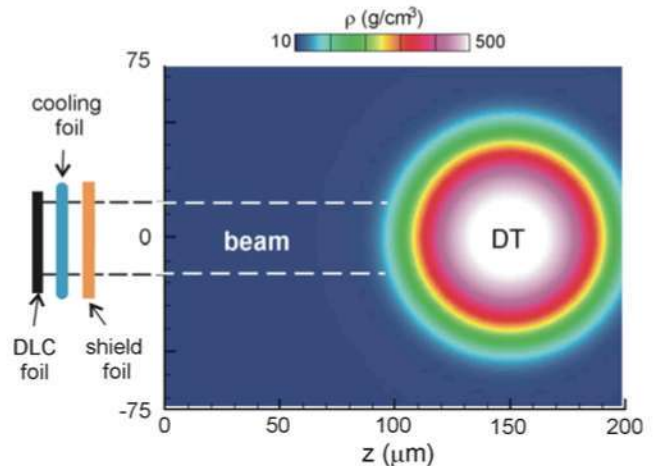


Fig. 1. (Color online) Density map of the fuel configuration considered in this work. The beam is perfectly collimated along the distance $d = 5 \text{ mm}$ from the ion source to the simulation box.

5 mm far from the simulation box, a re-entrant cone is not necessary and therefore it has not been included in the calculations. Shield and cooling foils (Huang *et al.*, 2011) have not been included either because they are too thin (around 10 μm each) to induce relevant ion energy losses. On the other hand, because the fuel is stagnated at the time of maximum compression, we assume that the DT is initially at rest with a uniform temperature of 100 eV. This corresponds to a ratio between the plasma pressure and the Fermi pressure of 2.21 at the peak density of 500 g/cm^3 .

Calculations have been performed with the 2-D radiation-hydrodynamics code SARA, that includes flux-limited electron conduction, multigroup radiation transport, ion energy deposition, DT fusion reactions, and α -particle transport (Honrubia, 1993a; 1993b). This code is also coupled to a hybrid model for fast electron transport in electron-driven fast ignition (Honrubia *et al.*, 2006).

2.1. Ion Pulse on Target

We assume that ions are generated instantaneously with a Gaussian energy distribution $f(E) \propto \exp\{-\log_2[(\epsilon - \epsilon_0)/\delta\epsilon/\epsilon_0]^2\}$ where ϵ_0 is the ion mean energy and $\delta\epsilon/\epsilon_0$ is the energy spread, chosen as 0.1 in this work. We refer to this distribution as “quasi-monoenergetic” throughout the paper. Instantaneous emission of the beam ions is assumed because the time of flight spread ($\approx 3 \text{ ps}$) is much longer than the ion acceleration times found for the BOA scheme. Yin *et al.* (2011a; 2011b) have shown that ions are accelerated mainly between the time of the foil relativistic transparency $n_e \approx \gamma n_c$ and the time when the target becomes undercritical ($n_{e,peak} \approx n_c$), where n_e and n_c are the electron density and the critical density, respectively, and γ is the relativistic Lorentz factor. For a 100 nm thick DLC (diamond like carbon) foil illuminated by a peak laser irradiance of $5.2 \times 10^{20} \text{ W/cm}^2$, Yin *et al.* obtained an enhanced

acceleration time of 400 fs, still negligible when compared with the time of flight spread shown in Figure 2. Anyhow, simulations taking into account the pulse duration mentioned above show no differences when compared with the instantaneous emission used here.

Beam power and ion kinetic energy on target of a 5 kJ quasi-monoenergetic carbon ion beam generated at a distance $d = 5$ mm are depicted in Figure 2. This distance has been chosen in order to have a peak power about 1.5 PW and a pulse duration on target of ≈ 3 ps (FWHM). Note that the small time spread of quasi-monoenergetic ions allows to place the source at much higher distances than Maxwellian ions. Because beam focalization over such distances may be difficult, a number of techniques have been proposed for that. Some of them are: (1) ballistic transport (Patel *et al.*, 2008; Key, 2007), (2) focusing by fields self-generated in hollow microcylinders by intense sub-picosecond laser pulses (Toncian *et al.*, 2006) and (3) focusing by magnetic lenses (Schollmeier *et al.*, 2008; Harres *et al.*, 2010, Hofmann *et al.*, 2011).

Focusing of ions with Maxwellian spectra has been studied in recent years. Kar *et al.* (2008) have demonstrated experimentally proton beam focusing by using foil rectangular or cylindrical hollow lens attached to a foil target. Offermann *et al.* (2011) have shown theoretically and experimentally that ion divergence depends on the thermal expansion of the co-moving hot electrons, resulting in a hyperbolic ion beam envelope. Using these results, Bartal *et al.* (2012) have shown experimentally an enhanced focusing of TNSA-protons in cone targets, inferring spot diameters about 20 μm for IFI conditions, well under the 40 μm spots required. However,

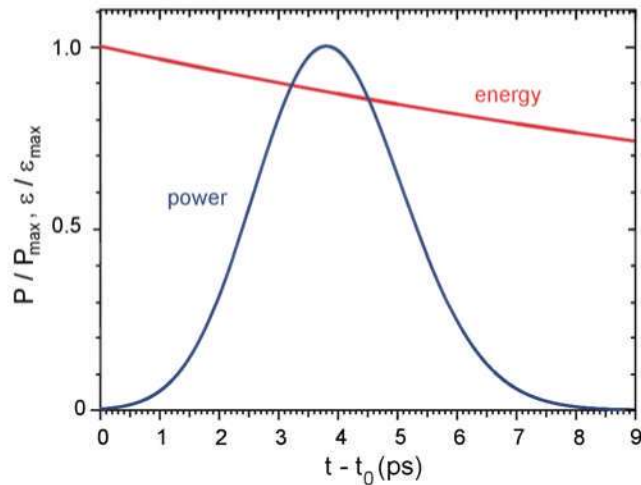


Fig. 2. (Color online) Beam power and ion kinetic energy at the left surface of the simulation box as a function of time. The incoming beam has a 5 kJ energy and a Gaussian spectrum centered at $\epsilon_0 = 450$ MeV with an energy spread of $\delta\epsilon/\epsilon_0 = 0.1$ (FWHM). The distance from the ion source to the left surface of the simulation box is $d = 5$ mm. Other parameters shown in the plot are $t_0 = 55$ ps, $\epsilon_{\text{max}} = 515$ MeV and $P_{\text{max}} = 1.5$ PW. The beam power and ion energy on target have been obtained by using the formulas shown by Temporal (2006).

as it has been shown recently by implicit PIC simulations (Qiao *et al.*, 2013).

For quasi-monoenergetic ions and, in particular, for those accelerated by the BOA scheme, Huang *et al.* (2011) have proposed recently the use of a second foil (see Fig. 1) to cool down the co-moving electrons and to absorb the trailing laser pulse that pass through the main foil after it becomes relativistically transparent (Huang *et al.*, 2011a; 2011b). The electron cooling obtained in this way reduces substantially both the beam divergence and the energy spread and can be used together with the methods mentioned above for beam focusing in order to get the required spot size on target. In addition, heavier ions are less sensitive than protons to the co-moving electron expansion.

2.2. Ion Stopping

Ranges of different ion species with typical energies for FI are shown in Figure 3 as a function of the DT plasma temperature. We have used the standard stopping power formalism for classical plasmas (Trubnikov, 1965; Honrubia, 1993b), which predicts range lengthening when plasma electron thermal velocities are comparable to fast ion velocity. The range lengthening effect is important for ions with Maxwellian energy distributions placed far from the target. It balances the reduction over time of the ion energy incident on the fuel, keeping the ion range almost constant (Temporal *et al.*, 2002). On the contrary, as the ion energy on target is approximately constant for quasi-monoenergetic ions, range lengthening increases the volume heated by the beam and thus the ignition energies. Fortunately, the importance of range lengthening is lower for heavier ions, as shown in Figure 3. For instance, protons increase their range by one order of magnitude when the DT temperature rises from 0.1 to 10 keV, while heavier ions such as aluminum or vanadium have an almost constant range for those temperatures. Thus, a better coupling of heavier ion beams with

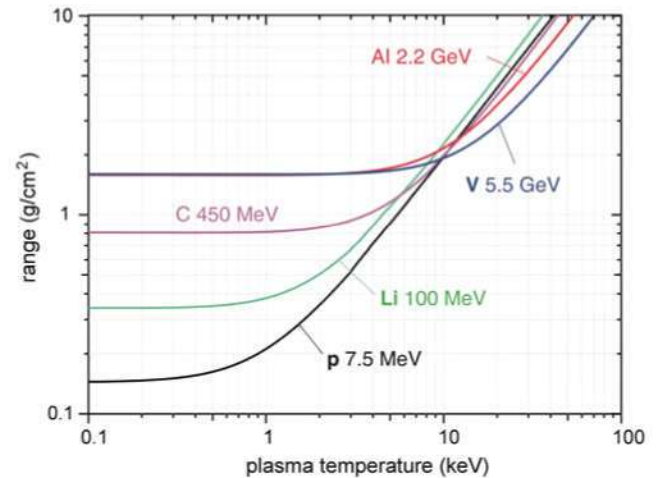


Fig. 3. (Color online) Range of monoenergetic ions in DT at 300 g/cm^3 as a function of the plasma temperature.

the plasma should be expected (Honrubia *et al.*, 2009). Note that the range of the ions shown in Figure 3 at 10 keV is about 2 g/cm^2 , higher than the 1.2 g/cm^2 requested for FI. However, as the ions deposit all their energy before such high temperatures are reached, the deposition range is substantially shorter in the cases analyzed here, as shown in Section 3.1.

It is worthwhile pointing out again that because the heavier the ion, the higher the energy they carry for a given range, the number of ions required for ignition decreases with the atomic number. It is lower by orders of magnitude for vanadium ions than for protons.

3. IGNITION ENERGIES FOR PERFECTLY COLLIMATED BEAMS

3.1. Energy Deposition

The energy deposition by lithium, carbon, and vanadium ion beams with different kinetic energies are compared in Figure 4. These energies have been chosen as those which minimize the ignition energies, as discussed in Section 3.3. Energy deposition has been computed by assuming that ions propagate in a straight line and thus neglecting the angular scattering by plasma ions, that is important for low energy ions only. Since the pulse duration is short enough compared to the resulting DT expansion (with exception of the cylindrical beam edge, where a shock wave is launched into the cold plasma), the volume heated by the beam is determined mostly by the ion energy and the range lengthening effect. The three beams shown in Figure 4 have a similar penetration into the dense core, almost up to its center. It corresponds to an areal density of around 1.6 g/cm^2 , higher than Atzeni's prescription of 1.2 g/cm^2 (Atzeni, 1999, Atzeni *et al.*, 2002) due to the energy deposition in the coronal plasma. Lithium ions show a much less localized energy deposition than heavier ions, such as vanadium, due to their higher range lengthening. Note also that the energy deposition in the coronal plasma decreases for heavier ions. Thus, the coupling efficiency (defined as the energy deposited in the plasma at densities higher than 200 g/cm^3) should be higher for heavier ions. In particular, for the lithium, carbon, and vanadium beams of Figure 4, the coupling efficiencies are 0.74, 0.81, and 0.89, respectively, well over the coupling efficiencies found for ions with a Maxwellian energy distribution (Honrubia *et al.*, 2009).

3.2. Optimal Beam Radius

Ignition energies E_{ig} as a function of the beam diameter for different ion beams are shown in Figure 5. They have been obtained as the minimum beam energy for which the thermonuclear fusion power has an exponential or higher growth sustained in time. The ignition energies of all beams are quite close and have a similar variation with the beam diameter. The lowest ignition energy, 8.3 kJ, is obtained for

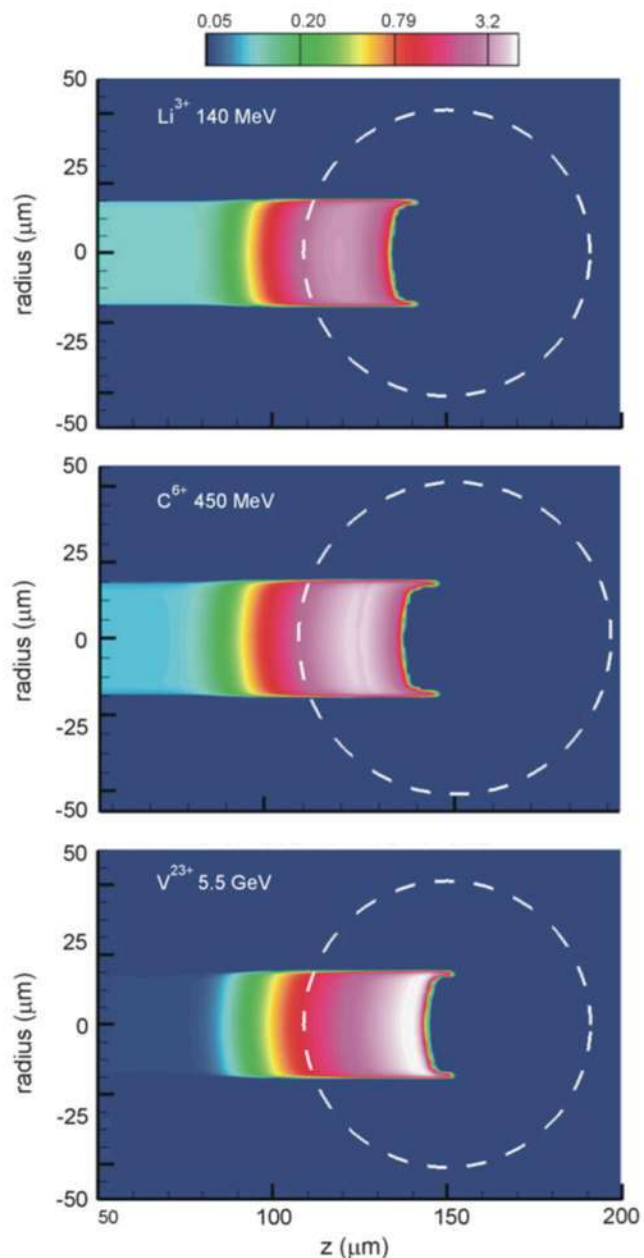


Fig. 4. (Color online) Energy density in units of 10^{11} J/cm^3 deposited in the target of Figure 1 by 8.5 kJ quasimonoenergetic beams (a) 140 MeV lithium ions, (b) 450 MeV carbon ions and (c) 5.5 GeV vanadium ions. The distance d from the ion source to the left surface of the simulation box is 5 mm for all beams. The dashed curves show the initial position of the density contour $\rho = 250 \text{ g/cm}^3$.

450 MeV carbon ions. In all cases, the ignition energies rise for lower and higher beam diameters, showing almost a plateau for diameters between 20 and 40 μm , which determines the focusing requirements for IFI. For beam diameters lower than 20 μm , the energy density deposited is very high, leading to a strong plasma expansion and range lengthening with the subsequent increase of ion penetration. Ions can even pass through the compressed fuel and escape off the rear surface. For beam diameters higher than 40 μm , the

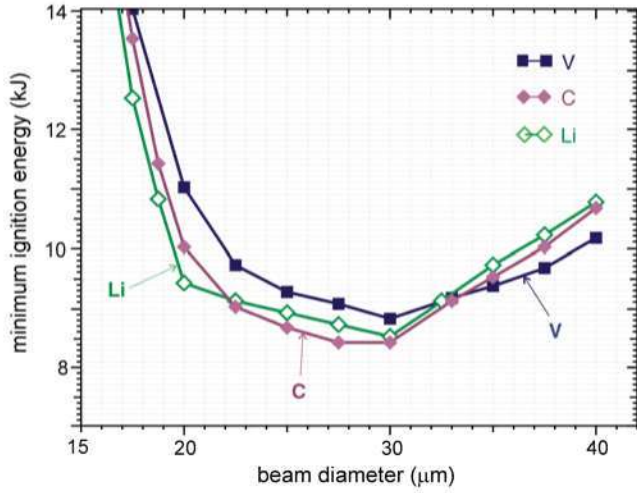


Fig. 5. (Color online) Minimum ignition energies of the target shown in Figure 1 heated by 100 MeV lithium, 450 MeV carbon and 5.5 GeV vanadium ions as a function of the beam diameter. All the beams have an energy spread of 10%. The source-core distance d is 5 mm.

ignition energies E_{ig} rise again due to the larger spot volume that has to be heated. However, the increase of the ignition energies is less than proportional to that volume due to the reduction of α -particle losses from large spots.

3.3. Optimal Ion Energies

The ignition energies for different beams as a function of the ion energy per nucleon are shown in Figure 6. It is interesting to point out the remarkable result that all the ions have similar ignition energies, around 8.5 kJ for the optimal kinetic energies ϵ_0 . These optimal energies increase with the atomic number, being 140 MeV for lithium, 450 MeV for carbon,

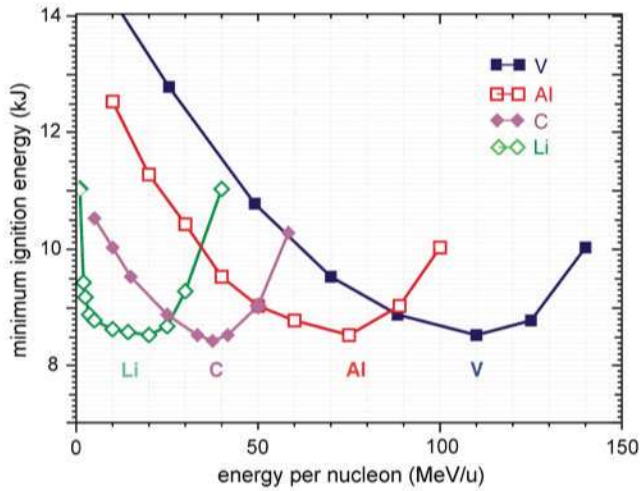


Fig. 6. (Color online) Minimum ignition energies of the target shown in Figure 1 heated by quasi-monoenergetic lithium, carbon, aluminum and vanadium ions as a function of the mean kinetic energy per nucleon. The source-target distance d is 5 mm, the energy spread $\delta\epsilon/\epsilon = 10\%$ and the beam diameter $30 \mu\text{m}$ in all cases.

2 GeV for aluminum, and 5.5 GeV for vanadium ions and scaling, approximately, as Z^2 . This scaling is important because it prescribes the optimal ion type as a function of the available ion-accelerating electric potential. The increase of the optimal ion energies with Z was also reported by Albright *et al.* (2008) and Fernández *et al.* (2008) within the context of IFI capsule designs for NIF.

The shape of the curves shown in Figure 6 can be explained by taking into account that for low ion energies ϵ_0 the pulse on target has a relatively low power, $P \propto \epsilon_0^{1/2}$ and a longer duration, $t_{pulse} \propto \epsilon_0^{-1/2}$ (Honrubia *et al.*, 2009). In this case, the pulse departs from the optimal one and the ignition energies E_{ig} increase. For high ion energies, E_{ig} increases again due to the higher fuel mass heated by the ion beam.

As was mentioned in Section 2.2, the rise of the optimal ion energy with the atomic number of fast ions leads to a strong reduction of the number of ions required for ignition. For instance, around 10^{13} vanadium ions of 5.5 GeV ions are required to ignite the target shown in Figure 1, which is three orders of magnitude lower than that required for the standard proton fast ignition scheme (Roth *et al.*, 2001).

4. IGNITION ENERGIES FOR ARRAYED BEAMS

In order to reduce the IFI beam requirements, we propose a new irradiation scheme aimed at improving the beam-target coupling and igniting the compressed core more efficiently than the single beam scheme discussed in Section 3. In addition, it may lead to a further reduction of the ion number. Basically, the scheme consists of using a set of beams generated far from the imploded core and focusing them into a spot placed in the density ramp surrounding the core. Crossing beams generate a hollow cone energy deposition pattern. The scheme is shown in Figure 7, where the ions are generated in a ring placed 5 mm far from the core with a mean diameter of 2.7 mm and a tilting angle of 15° . In the reference case discussed below, we consider $N = 10$ ion beams generated in spots placed symmetrically at the ring with a radius $r_{spot} = 20.3 \mu\text{m}$ and area $S = \pi r_{spot}^2$ each. We assume that $N = 10$ beams are sufficient to have an almost homogeneous ion ring on target, as shown by Temporal *et al.* (2009). To illustrate the new scheme and show the advantages of more tightly focused ion beams, laser beam parameters close to those used in recent BOA experiments and simulations have been chosen. Thus, we assume a laser intensity of $I_L = 10^{21} \text{ W/cm}^2$ and a laser-to-ion conversion efficiency $\eta = 10\%$. The laser power is $P_L = NI_L S$, the laser pulse energy is $E_L = E_{ig}/\eta$, and the laser pulse duration is $\tau = E_{ig}/(NI_L S \eta)$. For $E_{ig} = 6.5 \text{ kJ}$, one obtains $P_L (PW) = 13 \times N$, $E_L = 65 \text{ kJ}$, and $\tau (ps) = 5/N$. For the reference case $N = 10$ ion beams, each has a power $P_{beam} = 0.65 \text{ PW}$ and an energy $E_{beam} = 0.65 \text{ kJ}$. The pulse duration would be $\tau = 0.5 \text{ ps}$, and the carbon ion mean energy 500 MeV. Lower beam powers

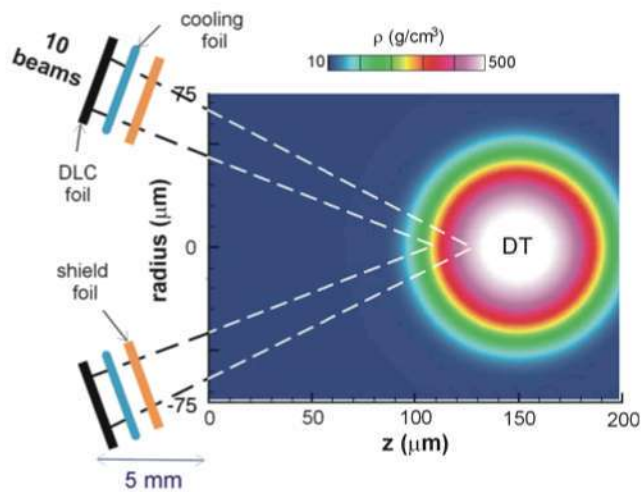


Fig. 7. (Color online) Sketch of the arrayed beams illumination scheme. Ten laser beams impinge on a ring located 5 mm far from the dense core. The ion beams generated at the rear target surface are focused on a 10 μm spot placed in the density ramp in order to generate a hollow cone energy deposition pattern.

can be obtained with longer laser pulses, that have not been studied theoretically nor experimentally yet.

The evolution of the target shown in Figure 7 can be summarized as follows. The beams are focused into a spot placed in the density ramp such that the ions still have enough energy to penetrate further into the compressed fuel (see Figs. 8a and 8b). Most of the energy deposition in the high density fuel takes place in a hollow cone. The dense fuel within the deposition zone expands and launches a strong shock wave that propagates toward the axis, where the shocks collide and compress the fuel further to very high densities ($\approx 1200 \text{ g/cm}^3$) (see Fig. 8c). The pressure peaks there (see Fig. 8d) and increases its strength while propagating toward the right (see Figs. 8e and 8f). Ignition starts in this high-pressure region (see Figs. 8g and 8h) and propagates through the dense and cold fuel (see Figs. 8i and 8j). In this irradiation scheme, ignition is produced by the collision of two shocks on the axis, not by the direct heating of the fuel, being in this sense a variant of the shock ignition scheme (Betti, 2006). The main advantage of this irradiation scheme is that ignition can be achieved with substantially lower beam energies. For instance, a beam of 500 MeV carbon ions focused onto a 10 μm spot diameter at the depth of $z = 100 \mu\text{m}$ on the axis requires 5.7 kJ for ignition, which is approximately 2/3 of the energy required for a single beam, as shown in Figure 5. It is worthwhile to emphasize that this improvement is not due to a sharper ion-beam focusing *per se*, as clearly shown in Figure 5 for a single beam. Contrary to the single-beam case, the success of the array scheme depends on a sharper focusing of the ion beams able to generate strong converging shock waves. For instance, if the beams could be focused into a 5 μm spot, the ignition energy would be reduced to 4.5 kJ, roughly a half of that obtained for a single beam. The dependence of the ignition energy on the spot diameter

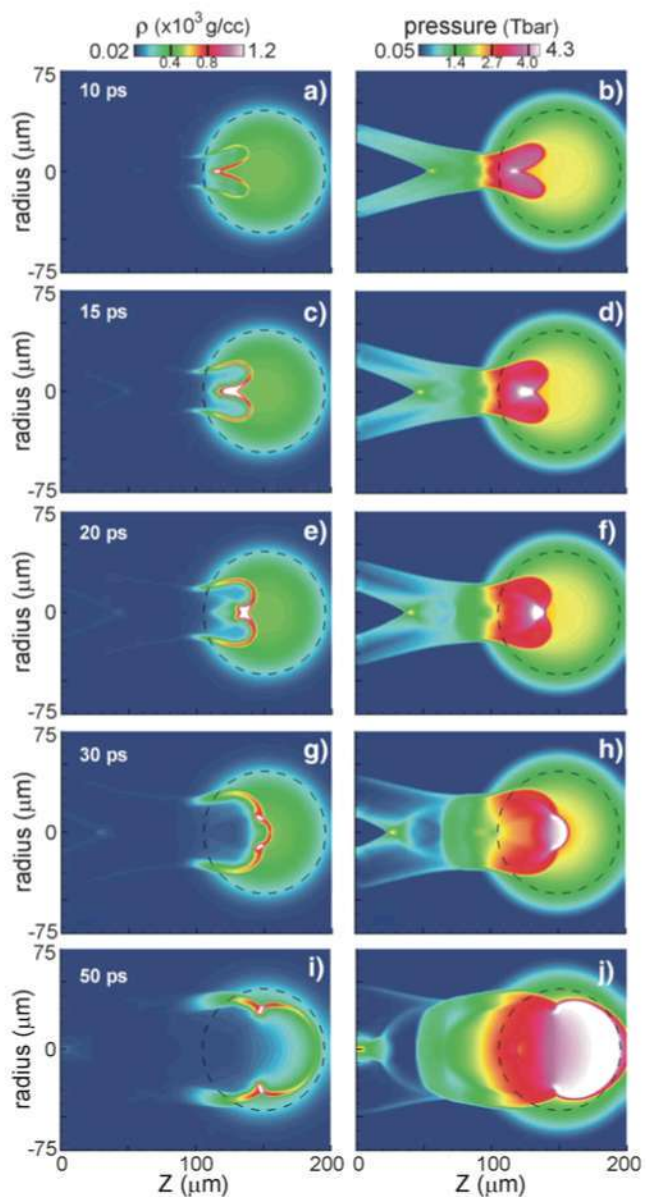


Fig. 8. (Color online) Ion density (left panels) and pressure (right panels) evolution of the target shown in Figure 7 heated by carbon ion beams of 500 MeV and $\delta\epsilon/\epsilon = 0.1$ focused onto a 10 μm spot sited at $z = 100 \mu\text{m}$. Ignition is produced by the shock waves launched by the ion beams that collide on the axis.

is shown in Figure 9. For diameters as large as 15 μm , the focusing beams scheme still reduces the ignition energy by $\approx 20\%$ when compared with the single beam scheme. For larger diameters, the differences between both schemes are not high enough to balance the difficulties of beam focusing. Thus, its practical implementation is limited by the possibility of beam focusing into 10 μm spots, smaller than those required for single beams (30 μm), from distances of millimeters, which is a challenging task.

The focused beams scheme presented above has some advantages when compared with that described in Temporal *et al.* (2008; 2009) for proton FI. In this latter scheme, the

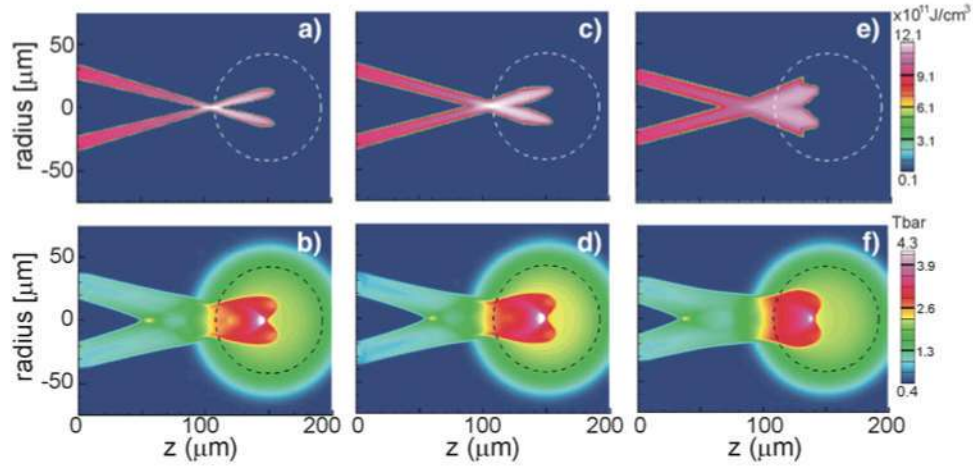


Fig. 9. (Color online) Sensitivity of the target heating on beam focusing. Energy deposition of 500 MeV carbon ion beam is shown in the upper panels and DT pressure at 15 ps in the lower panels. The focusing parameter d_{foc} , defined as the overlapped minimum beam diameter on axis, and the ignition energies E_{ig} are: (a, b) $d_{foc} = 5 \mu\text{m}$, $E_{ig} = 4.5 \text{ kJ}$; (c, d) $d_{foc} = 10 \mu\text{m}$, $E_{ig} = 5.7 \text{ kJ}$; and (e, f) $d_{foc} = 15 \mu\text{m}$, $E_{ig} = 7 \text{ kJ}$.

imploded target is first irradiated by a number of proton beamlets with an annular set up and a total energy of 1 kJ followed, after a time delay, by a second cylindrical beam of 7 kJ. The penetration of the central part of the cylindrical beam is blocked by the higher densities generated on the axis by the annular beamlets. Meanwhile the outer part of the cylindrical beam penetrates further and generates a cylindrical shock that collides on the axis and ignites the DT fuel ahead the energy deposition of the central part of the ion beam. On the contrary, in our scheme, the shocks are produced directly by the whole beam energy deposition without any blocking effect and thus the scheme should be more effective. In addition, in the scheme of Temporal *et al.* (2009), ignition is very sensitive to the time delay between the annular beams and the main cylindrical beam while in ours all beams are fired simultaneously. It is also worth noting that the focusing requirements are similar in both schemes because the diameter of each beamlet is $10 \mu\text{m}$, just the same than the spot required for our beams array.

5. CONCLUSIONS

In order to extend the possibilities of IFI with quasi-monoenergetic ions, we consider different ion species and propose a new irradiation scheme with arrayed beams. Specifically, fast ignition by quasi-monoenergetic lithium, carbon, aluminum, and vanadium ions have been analyzed for a simplified DT fuel configuration with a peak density of 500 g/cm^3 . Using middle or heavy ion beams has the advantage of reducing substantially, by orders of magnitude, the number of ions required for ignition. Ideal ion beams with a uniform flux within its cross section and an energy spread of 10% perfectly focused into such a configuration have been analyzed. Simulations show that the minimum ignition energies, about 8.5 kJ, are similar for the ions studied here despite

being obtained with very different kinetic energies. We should point out that those ignition energies have to be considered as a lower limit due to the strong assumptions made. Anyhow, taking into account laser-to-ion conversion efficiencies around 10% or higher found so far (Hegelich *et al.*, 2011), it would be possible to fast ignite a pre-compressed target with laser energies of about 100 kJ. It is worth mentioning the high laser-to-proton conversion efficiencies (15%) measured recently in target normal sheath acceleration experiments (Brenner *et al.*, 2014).

In addition to the collimated beam studies, we propose a new target irradiation scheme based on an array of focused quasi-monoenergetic ion beams. As a single 100 kJ short-pulse laser cannot easily envisaged, the single beam scheme would be based on the combination/superposition of multiple beamlets to get the required energy, in a similar way that the ion beam array proposed here. The difference is that in our scheme the beamlets should be focused onto a spot sited on the target density ramp. That may be a better way of deploying individual FI laser beams (or individual clusters of laser beams).

Our results show that the arrayed beam scheme reduces substantially the ignition energies obtained for single beams, provided that the ion beams can be adequately focused into $10 \mu\text{m}$ spots. Of course, to achieve such focusing will require a substantial reduction of the transverse temperature of co-moving electrons, for instance, by using a second cooling foil (Huang *et al.*, 2011), which shall be used together with one of the focusing techniques outlined in Section 2.1. The price to be paid for the reduction of the ignition energy would be the 3-D focusing of the beam array, which may have a similar or even higher difficulty than using lasers with energies above 100 kJ.

Future studies of IFI will include realistic beam and target configurations, and longer laser pulses in order to obtain more accurate estimations of the laser and ion beam requirements.

ACKNOWLEDGMENTS

This work was partially supported by the research grant ENE2009-1168 of the Spanish Ministry of Education and Research, was undertaken as part of the HiPER preparatory project, and used resources and technical assistance from the CeSViMa HPC Center of the Polytechnic University of Madrid. This work was also partially supported by the LDRD program at Los Alamos National Laboratory, and by the US DOE.

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