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Fast ignition by quasimonoenergetic ion beams

J.J. Honrubia[1], C.D. Enriquez[1], J.C. Fernández[2] and M. Hegelich[2]

[1] *ETSI Aeronáuticos, Technical University of Madrid, 28040 Madrid, Spain*
[2] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

Abstract. The potential of quasimonoenergetic ion beams for fast ignition (FI) of fusion targets is investigated. Lithium, carbon, aluminium and vanadium ions have been considered here to determine the optimal kinetic energy for each ion type. Our calculations show that the ignition energies of those beams impinging on a standard fuel configuration are similar. However, they are obtained for very different ion energies. Assuming that the ions can be focused onto 10 μm spots, a new irradiation scheme that reduces substantially the ignition energies is proposed. The combination of using intermediate ions, such as 5.5 GeV vanadium, and the new irradiation scheme allows one to reduce the number of ions required for ignition by roughly three orders of magnitude when compared with the standard proton FI scheme.

1. INTRODUCTION

We report here our progress in ion fast ignition (IFI), first proposed by Tabak et al. [1, 2], and more specifically on fast ignition driven by mononenergetic ion beams [3]. These ions can be generated by either 'laser-breakout afterburner' (BOA) [4–6], radiation pressure acceleration' (RPA) [7] or ion soliton (IS) [8] schemes, where very thin foils, <100 nm thick, are illuminated by sub-picosecond laser pulses with irradiances of 10^{21}, 10^{22} and 10^{20} W/cm^2, respectively. The BOA scheme uses linearly polarized light while the RPA and IS schemes use circularly polarized light. Monoenergetic ion beams have several advantages such as their better coupling with the compressed fuel [9] and the possibility to locate the ion source far from the target, i.e. re-entrant cones are not necessary. The progress of IFI with monoenergetic ions has been summarized recently by Hegelich et al. [10] pointing out the experimental demonstration of the required i) particle energies (400–500 MeV), ii) energy spreads (10–20%) [11] and iii) conversion efficiencies (>10%). The chance for the forthcoming years is to achieve experimentally all this simultaneously, very likely in new laser facilities.

We study here the ignition energies of different ion beams impinging on pre-compressed Deuterium-Tritium (DT) targets. This allows us to determine the optimal ion type as a function of its energy. Next, a new irradiation scheme with a set of ion beams focused on the imploded DT fuel is proposed. This scheme reduces substantially the ignition energies, provided that the ion beams can be focused onto 10 μm spots. Finally, conclusions and future work are outlined.

2. SIMULATION MODEL

We assume perfectly collimated cylindrical ion beams (constant flux within its cross section) impinging on an ideal configuration of compressed DT fuel with a peak density of 500 g/cm^3. The simulation box used in our simulations is shown in Fig. 1(a). Ions come from the left and propagate towards the dense DT through a low density plasma. Calculations have been carried out with the radiation-hydrodynamics code SARA [12]. We assume that ions are generated instantaneously with a Gaussian energy distribution

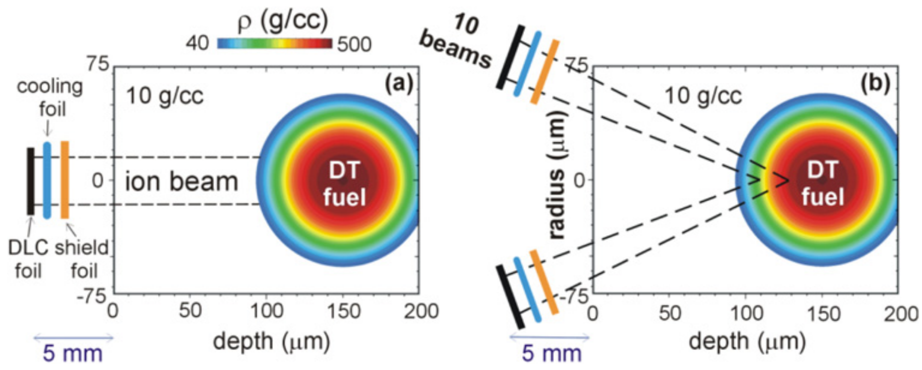

Figure 1. Density map of the compressed fuel configuration used in this work. (a) single beam irradiation, (b) focused beams irradiation.

and an energy spread of 10%. We refer to this last distribution as "quasimonoenergetic". Instantaneous emission of the beam ions is assumed because the time-of-flight spread (≈3 ps) is much longer than the ion acceleration times found for the BOA scheme. Yin et al. [3, 4] have shown that enhanced ion acceleration takes place between the time of the foil relativistic transparency, $n_e \approx \gamma n_c$, and the time when the foil becomes undercritical, $n_{e,peak} \approx n_c$, n_e and n_c being the electron density and the critical density, respectively, and γ the relativistic Lorentz factor. For a 100 nm thick diamond like carbon (DLC) foil illuminated by a peak laser irradiance of 5.2×10^{20} W/cm^2, Yin et al. obtained an enhanced acceleration time of 400 fs, still negligible when compared with the time-of-flight spread on target.

One of the advantages of quasimonoenergetic ions is that the ion source can be placed relatively far away form the compressed fuel. Because beam focalization over millimetre or higher distances may be difficult, a number of techniques have been proposed, such as ballistic transport [13, 14], focusing by fields generated in hollow microcylinders by intense sub-picosecond laser pulses [15] and focusing by magnetic lenses [16–18]. The divergence of TNSA-accelerated carbon ions has been analyzed experimentally and theoretically by Offermann et al. [19] showing that the divergence angle depends on the thermal expansion of the co-moving hot electrons, resulting in a hyperbolic ion beam envelope. Huang et al. [20] have proposed the use of a second foil 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. The electron cooling obtained in this way reduces substantially both the beam divergence and the energy spread. It could be used together with the methods pointed out above for beam focusing, e.g. ballistic focusing by curving the rear surface of the cooling foil, in order to get the required spot size on target. Despite the following scheme is not appropriate for transport distances of a few millimetres, it is worth mentioning the experimental demonstration of proton beam focusing by using foil targets with a rectangular or cylindrical hollow lens attached [21] or in hollow cones [22]. Bartal et al. have shown proton beam focusing enhancement in cone targets, predicting spot diameters about 20 μm for IFI conditions, well under the 40 μm spots required [22].

3. IGNITION ENERGIES FOR THE SINGLE BEAM SCHEME

We start by determining the optimal beam characteristics, diameter and mean kinetic energy for different ion species. Ignition energies E_{ig} as a function of the beam diameter are depicted in Fig. 2. They have been obtained as the minimum beam energy for which the thermonuclear fusion power has an exponential or higher growth sustained in time. Note that the ignition energies of the three ion species analyzed are quite close. The lowest value, 8.3 kJ, is obtained for 450 MeV carbon ions with a beam diameter of 30 μm. The ignition energies increase for lower and higher diameters, showing almost a

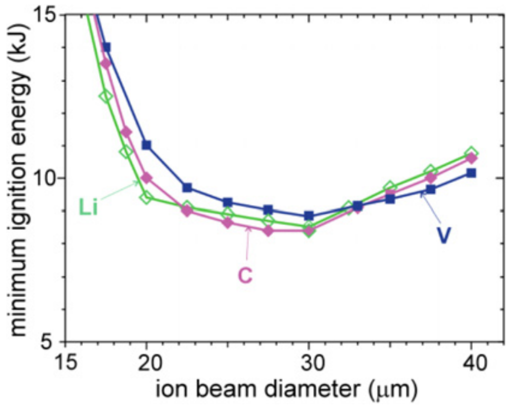

Figure 2. Ignition energies of the target shown in Fig. 1(a) heated by 100 MeV Li, 450 MeV C and 4.5 GeV V ions versus beam diameter.

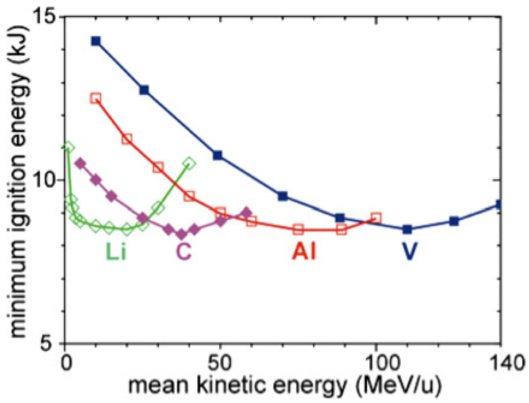

Figure 3. Ignition energies of the target shown in Fig. 1(a) heated by quasimonoenergetic Li, C, Al and V ion beams as a function of the ion energy per nucleon. The beam diameter is 30 μm.

plateau between 20 and 40 μm. For beam diameters lower than 20 μm, the energy density deposited is very high, leading to a strong plasma expansion and the subsequent increase of ion penetration. Ions can even pass through the compressed fuel and escape by the target rear side. For beam diameters higher than 40 μm, the ignition energies increase due to the larger volume that has to be heated. However, this increase is less than proportional to the volume due to the higher α-particle energy deposition. We can conclude from Fig. 2 that beam diameters on target between 20 and 40 μm are required.

The ignition energies E_{ig} for different beams as a function of the specific ion energy are shown in Fig. 3. Defining the optimal ion energy ε_0 as that for which the minimum E_{ig} is obtained, the shape of these curves can be explained as follows. For kinetic energies lower than ε_0, the pulse has a relatively low power, $P \propto \varepsilon^{1/2}$, and long duration, $\tau \propto \varepsilon^{-1/2}$ [9], separating from the optimal shape and increasing E_{ig}. For higher kinetic energies, E_{ig} increases again due to the higher fuel mass heated by the ion beam.

It is worth pointing out the remarkable result that all the beams have similar ignition energies, $E_{ig} \approx 8.5$ kJ, for the optimal ion energies ε_0. These energies are 140 MeV for lithium, 450 MeV for carbon, 2.4 GeV for aluminium and 5.6 GeV for vanadium. This result agrees with that obtained in Ref. [23] and is important because it allows one to select the optimal ion type for a given ion energy. Note that the increase of the optimal ion energy for heavier ions leads to a strong reduction of the number of ions required for ignition, around 10^{13} for 5.6 GeV vanadium ions, which is three orders of magnitude lower than those required for the standard proton fast ignition scheme [24].

4. IGNITION ENERGIES FOR THE FOCUSED BEAMS SCHEME

This scheme consists in using a set of N beams generated far from the target and focused into a spot located in the density ramp surrounding the imploded fuel. The beams cross each other at the spot, creating a hollow cone energy deposition pattern in the core. A sketch of the irradiation scheme is shown in Fig. 1(b), where the ions are generated in a ring located 5 mm far from the fuel with a diameter of 2.68 mm and a tilting angle of 15°. In the reference case discussed below, we consider $N = 10$ ion beams generated in spots located symmetrically at the ring with a radius $r_{spot} = 20.34\,\mu$m and an area $S = \pi r_{spot}^2$. We suppose that $N = 10$ beams is sufficient to have an almost homogeneous ion ring on target. Assuming a laser intensity consistent with the BOA scheme $I_L = 10^{21}$ W/cm^2 and a laser-to-ion conversion efficiency $\eta = 10\%$, the laser power is $P_L = N I_L S$, the laser pulse energy $E_L = E_{ig}/\eta$ and the laser pulse duration $\tau = E_{ig}/(N I_L S \eta)$. For $E_{ig} = 6$ kJ, one obtains $P_L(\mathrm{PW}) = 13N$, $E_L = 60$ kJ

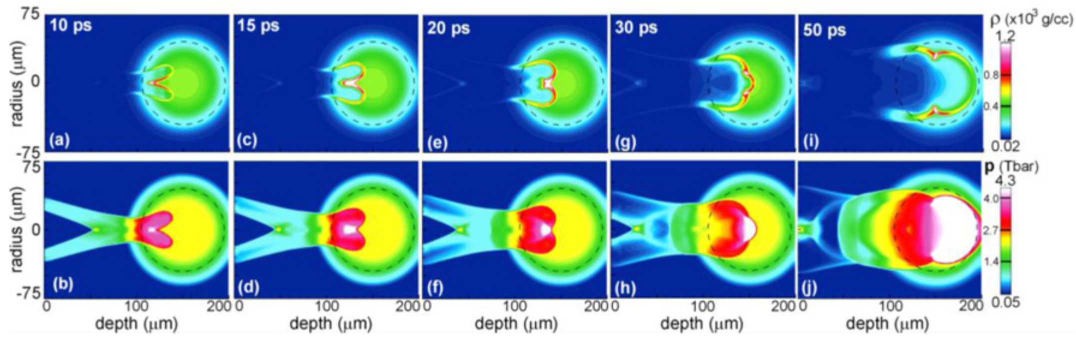

Figure 4. Ion density (top panels) and pressure (bottom panels) evolution of the target shown in Fig. 1(b) heated by 500 MeV C ions. The beam energy is 5.7 kJ.

and $\tau(\text{ps}) = 4.6/\text{N}$. For the reference case of $N = 10$ beams, the laser beam parameters are a power per beam $P_{L,beam} = 13$ PW with a pulse duration $\tau = 0.46$ ps and a beam energy $E_{L,beam} = 0.6$ kJ.

The evolution of the target heated by focused beams is shown in Fig. 4. It can be summarized as follows. The beams are focussed to a spot at the density ramp such that the ions still have enough energy to penetrate further in the compressed fuel, as depicted in Figs. 4(a) and (b). Most of the energy deposition in the high density fuel has a hollow cone shape. The dense fuel located in this zone expands and launches a strong shock wave that propagates towards the axis, where the shocks collide and compress further the fuel to very high densities ($\approx$1200 g/cm^3), as shown in Fig. 4(c). The pressure peaks there, Fig. 4(d), and increases its strength while propagating towards the right, Figs. 4(e) and (f). Ignition starts at this high-pressure region, Figs. 4(g) and (h), and propagates towards the dense and cold fuel. In this irradiation scheme, ignition is produced by the collision of two shocks at the axis and not by direct fuel heating, being in this way a kind of shock ignition. The main advantage of this 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 at a depth of $z = 95\,\mu$m on the axis requires 5.7 kJ for ignition, approximately 2/3 of the ignition energy of a single beam shown in Fig. 2. The ignition energy can be reduced further if the ions can be focused onto a smaller spot. For instance, if the beams can be focused to a 5 μm spot, the converging shocks are stronger and the ignition energy is reduced to 4.5 kJ, roughly a half of that obtained for a single beam. On the contrary, the ignition energies tend to those found for a single beam for higher focusing diameters. Thus, the practical implementation of this scheme is bounded by the possibility of focusing the ion beams onto spots smaller (10 μm) than those required for single beams (30 μm) from distances of millimetres, which is a challenging task.

The focused beam scheme presented here has some advantages compared with scheme described in Ref. [25] for proton FI. In this scheme, the imploded target is first irradiated by a number of proton beams with a radial annular profile (1 kJ) followed, after a time delay, by a second cylindrical beam (7 kJ). The central part of the main cylindrical beam is tamped by the higher densities generated on the axis by the annular beam, while the outer part of the main beam generates a cylindrical shock that collide on axis and ignites the DT fuel. On the contrary, in our scheme, the shocks are produced directly by the full beam energy deposition without any tamping effect and thus the scheme should be more effective. In addition, in the scheme of Ref. [25], ignition is very sensitive to the time delay between the annular beams and the main beam while in our scheme all beams are fired simultaneously.

5. CONCLUSIONS

In previous works, we showed that quasimonoenergetic ions have a higher coupling efficiency and lower ignition energies than the standard FI scheme with Maxwellian ions [9]. Here, in order to explore the full potential of IFI, we have investigated the use of lithium, carbon, aluminium and vanadium quasimonoenergeticions to ignite a simplified DT fuel configuration with a peak density of $500\,\mathrm{g/cm^3}$. Ideal beams with a uniform flux within its cross section and an energy spread of 10% are perfectly focused onto such a configuration. Simulations show that the minimum ignition energies are similar for the ions studied here despite they are obtained for very different ion energies. We should point out that those ignition energies should be considered as a lower limit due to the strong assumptions made.

In addition to the single beam studies, we propose a new target irradiation scheme based on focused quasimonoenergetic ion beams. Our results show that this scheme reduces substantially the ignition energies obtained for single beams if ions can be focused onto 10 μm spots.

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