Fast ignition by laser-driven carbon beams

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Abstract. Two-dimensional simulations of ion beam driven fast ignition are presented. Ignition energies of protons with Maxwellian spectrum and carbon ions with quasi-monoenergetic and Maxwellian energy distributions are evaluated. It is found that quasi-monoenergetic ions have better coupling with the compressed Deuterium-Tritium and substantially lower ignition energies. These energies are similar to those found for relativistic electrons, provided that a laser to quasi-monoenergetic carbon ion conversion efficiency around 10% can be achieved.

Fast ignition by laser-driven ion beams [1] offers the advantages of the classical interaction of ion beams with compressed fuels, their much more localized energy deposition, and the stiffer ion transport with the possibility of beam focusing. Recent particle-in-cell (PIC) simulations have shown that circularly polarized pulses with irradiances around $10^{22}$ W/cm$^2$ can accelerate ions up to hundreds of MeV by means of radiation pressure. These ions have quasi-monoenergetic energy distributions, small divergence angles [2–5] and laser-to-ion conversion efficiencies around 10% [3]. The laser break-out afterburner scheme has been also proposed to generate almost perfectly collimated quasi-monoenergetic ions with conversion efficiencies of a few percent [6] at laser intensities about $10^{21}$ W/cm$^2$. These new schemes are suitable to accelerate ions heavier than protons to the energies required for fast ignition applications. Fernández et al. [7] suggested the use of quasi-monoenergetic carbon ions with kinetic energies of a few hundreds of MeV to ignite pre-compressed fusion targets. Use of heavier ions has been studied by Shmatov in in Ref. [8]. One advantage of quasi-monoenergetic ion beams is the possibility to place the source far from the compressed core avoiding the use of re-entrant cones. However, the feasibility of the carbon ion fast ignition scheme (CFI) relies on the demonstration of conversion efficiencies comparable to those found for protons. Here, we assume a laser to quasi-monoenergetic carbon ions conversion efficiencies of about 10% and compare the potential of the proton fast ignition (PFI) and CFI schemes.

We consider the ideal case of perfectly collimated cylindrical ion beams of 30 μm diameter impinging on a DT blob with a peak density around 500 g/cm$^3$. Scattering of ions by the background DT plasma has been neglected because it is small for temperatures lower than the ignition temperature (≈10 keV). The two different configurations of the compressed DT shown in figure 1 are assumed. The first one is a simplification of the configuration obtained from the 2D implosion calculations of cone-targets. The second one is similar to that obtained by Clark and Tabak [9] from 1D implosion calculations of a direct-drive target to get an almost isochoric configuration of the compressed fuel.
This target has 0.9 mg of DT that are compressed by a laser pulse of 485 kJ delivered in 34 ns [9]. The calculations shown below have been performed with the 2D radiation-hydrodynamics code SARA, which includes flux limited electron conduction, multigroup radiation transport, ion energy deposition, DT fusion reactions and \(\alpha\)-particle transport [10].

The simulation box is shown in figure 1. Ions come from the left and propagate towards the blob through low density plasma. We assume that ions are generated instantaneously with a Maxwellian energy distribution for protons (\(N(\varepsilon) = 2N_0\varepsilon^{1/2}\exp[-\varepsilon/kT]/\pi^{1/2}(kT)^{3/2}\), where \(N_0\) is the total number of ions and \(T\) their temperature) and a Gaussian energy distribution for carbon ions (\(N(\varepsilon) = N_0\varepsilon^{1/2}\exp[-\alpha((\varepsilon-\varepsilon_0)/\delta\varepsilon)^2]/\pi^{1/2}\delta\varepsilon\), where \(\alpha = 4 \ln(2)\), \(\varepsilon_0\) is the mean energy and \(\delta\varepsilon\) the full width at half-maximum, FWHM). If the energy spread is \(\delta\varepsilon/\varepsilon_0 = 0.1\), we refer to this last distribution as “quasi-monoenergetic”. We assume Instantaneous emission of the beam ions because the spread of the time of flight from the source to the target (\(\approx 10\) ps) is much longer than the typical ion acceleration time (\(\approx 1\) ps). We used analytical formulas [11] to compute the kinetic energy and the beam power on target of ions accelerated instantaneously at a distance \(d\). Beam power and ion kinetic energy of 10 kJ Maxwellian proton beam generated at \(d = 0.5\) mm and quasi-monoenergetic carbon ion beams generated at \(d = 1.35\) cm are shown in figure 2. These two distances have been chosen in order to have the same peak power and approximately the same pulse duration on target (\(\approx 8\) ps) with both beams. It is worth noting that the almost negligible time spread of ions with quasi-monoenergetic energy distributions allows to place the source at much higher distances \(d\) than Maxwellian ions. Because beam focalization over distances of a few centimeters may be difficult, several focusing techniques have been proposed such as: i) ballistic transport [12], ii) focusing by fields self-generated in hollow microcylinders by intense subpicosecond laser pulses [13] and iii) focusing by magnetic lenses [14].

We assume that, ideally, ion beams are perfectly collimated without any divergence at the source and during the transport towards the compressed fuel.

![Figure 1](image1.png)  
**Figure 1.** Density isocontours and radial profiles of the targets considered. (a) Super-Gaussian density blob and (b) density distribution taken from Fig. 8 of Ref. [9].

![Figure 2](image2.png)  
**Figure 2.** Beam power and ion kinetic energy at the left surface of the simulation box as a function of time. The dashed line corresponds to a Maxwellian proton beam with \(T_p = 4\) MeV, \(d=0.5\) mm, \(t_0=0\), \(\varepsilon_{\text{max}} = 58\) MeV and \(P_{\text{max}} = 1.12\) PW. The solid line corresponds to a Gaussian carbon ion beam with \(\delta\varepsilon/\varepsilon_0 = 0.1\), \(d=1.35\) cm, \(t_0 = 158\) ps, \(\varepsilon_{\text{max}} = 458\) MeV and \(P_{\text{max}} = 1.12\) PW.
with high kinetic energies per nucleon. For instance, the range of 400MeV carbon ions increases by a factor of \(~\approx 3\) for plasma temperatures from hundreds of eV to 10 keV, while this factor is around 20 for 5 MeV protons [15].

The ignition energies \(E_{ig}\) as a function of proton temperature and kinetic energy of carbon ions are shown in figures 3(a) and (b), respectively. They have been obtained as the minimum beam energy for which the thermonuclear fusion power has an exponential or higher growth sustained in time. We found an optimal proton temperature \(T_p\) around 4 MeV, for which \(E_{ig} = 12.7\) kJ. This energy is higher than the \(~9\) kJ found in Ref. [16] for an ideal isochoric fuel configuration with a DT density of 500 g/cm\(^3\) and the same source – target distance \(d = 0.5\) mm. This difference accounts for the energy deposited in the plasma surrounding the dense fuel. For the same ideal isochoric configuration used in the reference, our simulations give \(E_{ig} = 9.5\) kJ, in good agreement with [16]. This result evidences the importance of the plasma surrounding the dense fuel, which increases substantially ignition energies. The details are given in Ref. [15].

Quasi-monoenergetic carbon ions (\(\delta\varepsilon/\varepsilon_0 = 0.1\)) have a better coupling with the dense fuel. Figure 3(b) shows that ignition energies are around 9.5 kJ for the optimal energy range from 25 to 40 MeV/u, which are about 25% lower than those obtained for Maxwellian protons. Similarly to PFI, the ignition energies can be reduced further by removing the coronal plasma surrounding the dense core. For "ideal" isochoric targets, \(E_{ig}\) is reduced to 8 kJ for 15 – 32 MeV/u ions. It is interesting to note that the effect of the surrounding plasma on \(E_{ig}\) is more pronounced for ion energies lower than 25 MeV/u. Maxwellian carbon ions have ignition energies much higher than quasi-monoenergetic ions and comparable to those found for Maxwellian protons.

Ignition energies of quasi-monoenergetic carbon ions with different energy spreads \(\delta\varepsilon/\varepsilon_0\) heating the imploded fuel configuration shown in figure 1(b) are plotted in figure 3(c). It is remarkable that these energies are at least 25% higher than those obtained for the target with the super-Gaussian density distribution of figure 1(a). This is mainly due to the energy deposition in the plasma.
surrounding the core, as can be evidenced by comparing the ignition energies with those obtained for the ideal isochoric configuration. Note that the effect of the surrounding plasma on $E_{ig}$ is particularly important for relatively low ion kinetic energies. Thus, the optimal energy range of quasi-monoenergetic carbon ions is shifted from the $25 − 40$ MeV/u obtained for the super-Gaussian density distribution to the $33 − 50$ MeV/u shown by the curve labeled with $\delta \varepsilon/\varepsilon_0 = 0.1$ in figure 3(c).

Ignition energies are very sensitive to the ion energy spread, as can be seen by comparing the curves labeled by $\delta \varepsilon/\varepsilon_0 = 0.1$ and 0.2 in figure 3(c). Energy spreads higher than 0.2 lead to high ignition energies >20 kJ for $\delta \varepsilon/\varepsilon_0 = 0.4$ and $d = 2$ cm. These energies can be reduced by placing the ion source closer to the target. For instance, the ignition energy of 50 MeV/u carbon ions with $\delta \varepsilon/\varepsilon_0 = 0.4$ generated at a distance $d = 0.5$ cm turns out to be $E_{ig} = 13.5$ kJ, slightly higher than the 12.5 kJ obtained for ions with the same kinetic energy, $\delta \varepsilon/\varepsilon_0 = 0.1$ and $d = 2$ cm. Yet, a source - core distance $d = 0.5$ cm is still high enough to use target designs without a re-entrant cone inserted. Therefore, we can conclude that the requirement of quasi-monoenergetic spectra can be relaxed in such a manner that ion beams with broad energy distributions generated relatively far from the compressed core can ignite realistic imploded fuel configurations with moderate beam energies. If the plasma surrounding the dense core is minimized or removed, these ignition energies could be reduced further.

In summary, the use of quasi-monoenergetic ions heavier than protons improves the beam coupling efficiency and reduces substantially the ignition energies. In addition, quasi-monoenergetic ions allow placing the ion source far away from the fuel capsule, simplifying target design and fuel implosion and compression, provided that ions can be focused onto a spot of about 30 $\mu$m over distances of a few centimeters. This conclusion is still valid for ion energy spreads as high as 40%. In this case, the increase of the ignition energy can be compensated by reducing the source – capsule distance, which is still high enough to avoid the use of re-entrant cones. Prior to the application of the fast ignition by quasi-monoenergetic ions scheme, laser to ion conversion efficiencies of the order of 10% have to be demonstrated experimentally. If these conversion efficiencies are achieved, our calculations show that the laser energy requirements are similar to those found for fast ignition driven by relativistic electrons. In this case, the advantages of the ion fast ignition scheme are attractive enough to envision ion fast ignition as a candidate to demonstrate fast ignition in future facilities such as HiPER [17].

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