FAST IGNITION OF FUSION TARGETS INDUCED BY ION BEAMS

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Fast ignition by laser-driven ion beams [1, 2] offers the advantages of their classical interaction with the imploded fuel and the relatively moderate ignition energies compared to hot electrons. Proton fast ignition (PFI) is a promising option because of the high (≈ 12%) laser-to-proton conversion efficiencies found in experiments [3]. Quasi mono-energetic carbon ion beams have been proposed recently [4] as an alternative to the PFI scheme due to their better coupling with the compressed Deuterium-Tritium (DT) core and the lower ion currents required for ignition. However, the feasibility of the carbon ion fast ignition scheme (CFI) is conditioned by the experimental demonstration of conversion efficiencies comparable to those found for protons [4, 5].

Recent results of proton fast ignition show that the ignition energy can be reduced by using a sequence of two beams [6]. Moreover, fuel targets compressed up to 500 g/cm^3 can be ignited by two Maxwellian proton beams with a temperature T_p = 4 MeV and a total energy around 8 kJ [10]. Despite mono-energetic protons may have better coupling with the compressed core, the relatively low conversion efficiency found in experiments so far hampers its application to fast ignition. Assuming that Maxwellian protons can be generated with an efficiency of 12%, the laser energy required for ignition would be about 67 kJ @ ω_0 (λ = 1.053 μm), which is of the same order than the energies envisioned for future fast ignition facilities such as HiPER [7]. Here, we compare the PFI and CFI schemes to assess the potential of carbon ions for fast ignition applications.

1. Simulation model

We assume a perfectly collimated beam of 30 μm diameter impinging on a DT blob with a super-Gaussian density profile characterized by a peak density of 500 g/cm^3 and 82 μm diameter (FWHM). This configuration is based on implosion calculations of direct-drive targets with a cone inserted presented elsewhere [8]. The ion beam enters by the left surface of the simulation box, which is placed 150 μm from the blob centre, and propagates through DT at 10 g/cm^3, as shown in Fig. 1. We also assume that protons are generated instantaneously with a Maxwellian energy distribution. This approximation is reasonable if the time of flight between the proton source and the dense core is much longer than the proton generation time. Notice that due to the different times of flight of Maxwellian protons from the source to the blob, the proton beam has a time spread of tens of ps, which is crucial for ignition [2]. The decreasing kinetic energy with time of protons arriving at the target is balanced by their range lengthening as the DT is heated up, keeping nearly constant the proton range [2, 6]. On the contrary, carbon ions have a quasi mono-energetic energy distribution with only 10% energy spread and almost negligible time spread. This led us to assume a Gaussian pulse of 5 ps duration (FWHM) for the beam. Since the carbon ion kinetic energy on target is almost constant in time, range lengthening could raise ignition energies. This effect is, however, much less pronounced for carbon ions than for protons and therefore range lengthening is not very relevant in CFI. For instance, the range of 32 MeV/nucleon carbon ions increases by a factor of ≈2 for DT temperatures from 0.1 to 10 keV while the range of 5 MeV protons increases by a factor of ≈10 for the same temperatures.

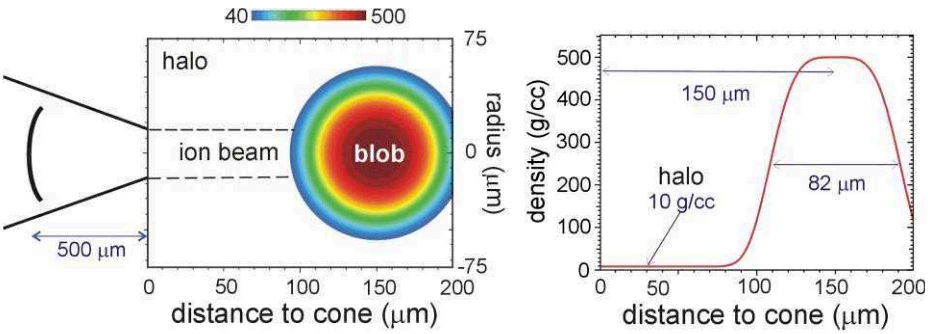

Figure 1. Density iso-contours and central cut of the compressed fuel used in our simulations. We assume that the ion source is located in the hollow cone depicted at the left, 500 μm from the surface of the simulation box.

Calculations have been performed with the 2-D radiation-hydrodynamics code Sara including flux-limited electron conduction, multigroup radiation transport, ion energy deposition, DT fusion reactions and α-particle transport [9].

2. **Ion beam energy deposition**

The energy deposited by the proton and carbon beams is shown in Fig. 2. It is worth noticing that the quasi mono-energetic carbon beam heats a volume smaller than the Maxwellian carbon and proton beams and ignites the DT with substantially lower energy. It is also remarkable that a significant fraction of the Maxwellian carbon beam energy is deposited in the density ramp despite the beam temperature T_p has been chosen to maximize the energy deposition in the dense core.

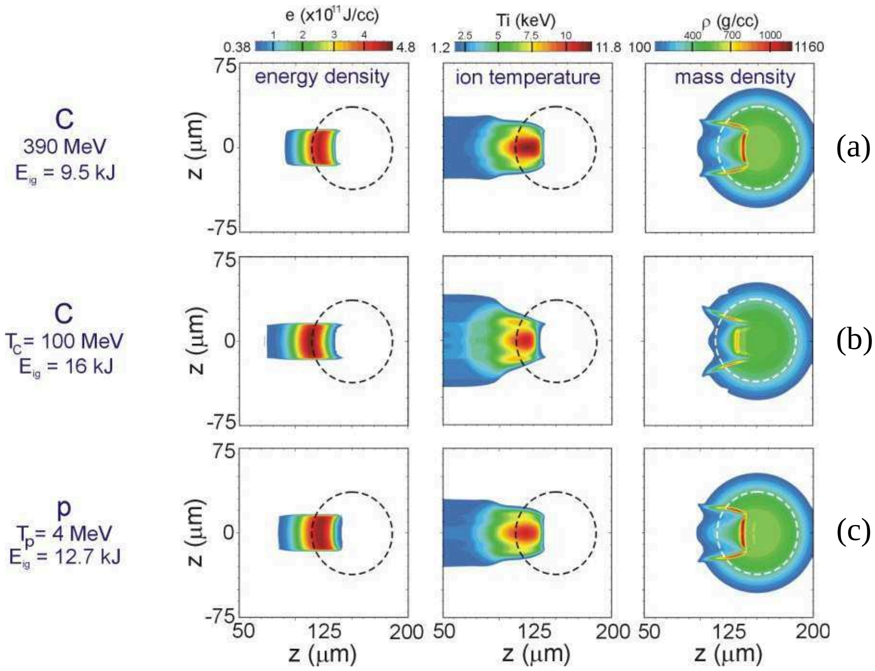

Figure 2. Energy density deposited by (a) a carbon beam with a mean kinetic energy of 32 MeV/nucleon and 10% of energy spread, the ignition energy is E_{ig} = 9.5kJ (b) carbon beam with a Maxwellian energy distribution and temperature T_C = 100 MeV, E_{ig} = 16 kJ, and (c) proton beam with a Maxwellian energy distribution and T_p = 4 MeV, E_{ig} = 12.7 kJ. DT density is higher than 250 g/cm^3 within the encircled areas.

3. Fast ignition by proton and carbon beams.

The ignition energies obtained for proton and carbon beams are shown in Fig. 3. Beam kinetic energy has been considered as parameter. We found optimal proton temperatures T_p around 4 MeV and optimal energies of carbon ions about 40 MeV/nucleon. The corresponding minimum ignition energies are 12.7 kJ for protons and 9.5 kJ for carbon ions. These ignition energies can be reduced increasing the target density as shown in Fig. 3(a), where the energies obtained for a peak density of 600 g/cm^3 are depicted. Recent implosion calculations of cone-targets show that it is possible to achieve densities as high as 600 g/cm^3 with 200 - 300 kJ of drive energy [8, 11]. Another possibility to reduce the ignition energy is to eliminate or minimize (in terms of ρr) the plasma surrounding the dense core. The ignition energies obtained assuming an 'ideal' isochoric blob without such plasma are shown in Figs. 3(a) and (b).

As was pointed out in Section 3, quasi mono-energetic carbon ion beams have better coupling with the compressed DT. Figure 3(b) shows ignition energies about 10 kJ for the optimal kinetic energy range of 30 – 40 MeV/nucleon. Those energies can be further reduced in isochoric targets up to, for instance, 7.5 kJ for 32 MeV/nucleon ions, which is comparable and even lower than the 8 kJ found for protons with T_p = 4 MeV using the two-pulse scheme

[10]. In addition, it is worthwhile noticing how the energy deposited in the surrounding plasma becomes important for energies of carbon ions lower than 30 MeV/nucleon, increasing substantially the ignition energies found for the 'ideal' spherical blob.

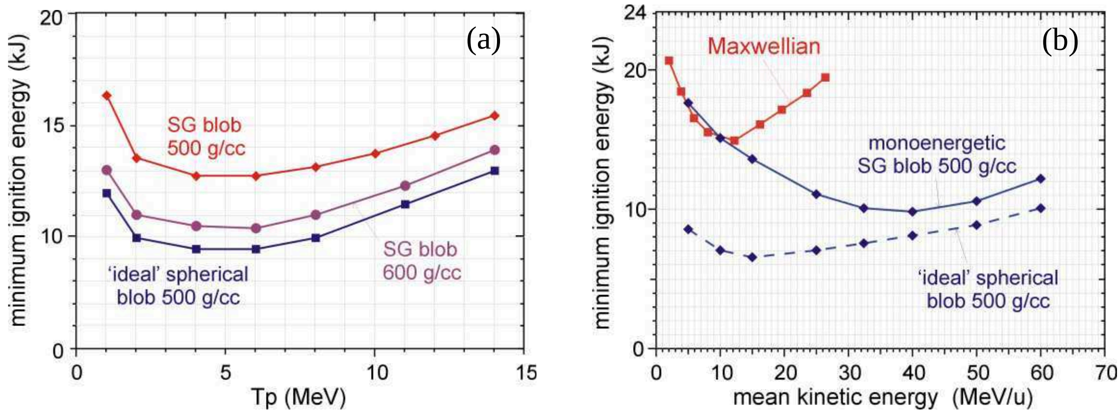

Figure 3. Ignition energies of the target shown in Fig. 1 heated by (a) proton and (b) carbon beams as a function of the temperature and specific beam kinetic energy, respectively. SG stands for supergaussian density profile with the peak density shown and 'ideal' for isochoric plasma.

4. Conclusions

Fast ignition driven by ions presents several advantages over fast ignition driven by electrons. In fact, the stopping power of ions is well known and it is possible to envisage the use of multiple beams [6] or to induce additional hydrodynamic compression of the DT [10] to further reduce ignition energies. Our calculations show that proton fast ignition can be achieved with lower ignition energies if the energy deposited in the surrounding plasma can be controlled by means of optimization of target implosion or using multiple proton beams. Carbon ion beams are a good candidate for fast ignition due to its good coupling with the compressed DT if laser to mono-energetic ion conversion efficiencies higher than 10% can be demonstrated experimentally.

Acknowledgements

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