Studies in Capsule Design for Mid-Z Ion-Driven Fast Ignition

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Abstract. Ion fast ignition (FI) is an approach to fast ignition inertial confinement fusion (ICF) where an energetic ion beam is used to heat a hot spot in a compressed ICF capsule to ignition conditions. Recent work at LANL and elsewhere suggests that ion beams with $Z > 1$ may be produced with characteristics suitable for FI. Indeed, fast ignition using mid-Z ions may have advantages over protons FI in terms of number of ions required for ignition, robustness of the ion beam to beam-plasma instabilities, sharpness of Bragg peak, and ability to locate the ion source far from the ignition capsule. In this paper, simple preliminary capsule designs for mid-Z ion fast ignition are assessed. These designs comprise a DT gas pocket, a DT ice fuel layer, and a low-Z ablator subject to a drive achievable on facilities such as the NIF and LMJ. Dependence of capsule gain with various beam parameters are obtained.

1. Introduction
Fast ignition [1] is an approach to fast ignition inertial confinement fusion whereby an external heating source is used to ignite a hot spot within a compressed ICF target. One advantage of fast ignition is that the hydrodynamic compression of the capsule occurs separately from the generation of the heat source, which means that it may be possible to achieve ICF ignition with less stringent requirements on capsule symmetry and convergence ratio. The traditional approach to fast ignition uses ultra-intense short-pulse lasers to generate hot electrons that propagate into and heat the target. In order to overcome electron beam divergence, a reentrant cone geometry is used to allow penetration of the laser into the ICF core. However, the presence of the cone complicates the capsule compression significantly, as hydrodynamic evolution and survival of the cone during compression are called into question.

An alternative approach to fast ignition is to use laser-generated proton beams [3, 2] to heat the target [4, 5, 6, 7]. Use of protons (and heavier ions [8], which may be generated with quasi-monoenergetic spectra [9, 10, 11, 12]) has several advantages. For instance, ions have a sharp Bragg peak and suffer less transverse scatter, so the hot spot can be more localized longitudinally and transversely, which reduces ion beam energy required. While most work on ion fast ignition has considered use of proton beams, recent work suggests that higher-Z ion beams, e.g., carbon, may have additional advantages. Such beams can, in principle, be focused to even smaller hot spots and require more energy per beam ion to penetrate into the ICF core. Therefore, higher-Z beams can be generated far from the target with fewer beam ions (thereby easing ion source surface area requirements) and can still penetrate into the core without the need for a reentrant
cone. This vastly simplifies the hydrodynamics of capsule implosions and, as we shall show, allows for the employment of overlapping beams.

In this paper, we show results of Lasnex [14] modeling of fast ignition using beams of fully ionized carbon ions. Unlike traditional ICF ignition, the hydrodynamics implosions we consider use modest convergence ratio, with peak average fuel density less than 150 g/cc. In this study, two counter-propagating ion beams are generated outside the capsule that travel along the axis of the capsule and deposit energy into a pair of hot spots. It is found that this two-beam configuration, for given beam mean energy, tends to produce higher gain than a single beam with the same total energy as the pair of beams. Moreover, in two-beam configurations the fusion yield is less sensitive to variation in beam parameters such as mean energy, energy spread, and stopping power.

2. Capsule Compression
The ICF capsule implosion in our modeling is driven by a simple temperature source set at fixed radius of 2 cm. The radiation temperature at the wall is driven by a 14.2 ns pulse comprising an initial pulse followed by a $T^{3.5}$ rise [15] that allows the fuel to move along the DT adiabat and achieve good compression given a fixed budget of energy. The capsule geometry is shown in the left panel of Fig. 1 with radiation drive profile shown in the right panel of Fig. 1. The capsule comprises a plastic shell of thickness 150 microns and outer radius 730 microns surrounding a DT ice layer of thickness 250 microns and a central pocket of DT gas. Outside of the capsule is a low density He fill gas between the capsule edge and the outer radius of the simulation. Under the conditions shown, the capsule absorbs 37.5 kJ of energy hydro phase and compresses to a peak average density of $\sim 150$ g/cc. The ignitor beam is launched into the capsule at time of peak density. Owing to the symmetry of the drive and the ignitor ion beams, the simulation geometry is of a quadrant of the capsule. While higher fuel density for this capsule can be achieved with higher drive energy, we use this implosion to study the effects of varying ion beam parameters.

3. Ion Beam Generation and Capsule Gain
In the simulations, the ignitor ion beam is launched from outside the capsule and directed along the axial symmetry axis. The beam is nearly columnar, a super Gaussian with exponent 10, with a 10 micron radius focus at the center of the capsule. Most of the simulations use C$^{6+}$ ions, but we also consider protons and V$^{23+}$ ions. The beam is assumed to a Gaussian spread in energy about a central energy with a specified standard deviation. These beam parameters are comparable to those obtained from the simulations by Yin et al. of the “laser break-out afterburner” process [12, 13].
The first examination is the effect of beam energy on gain, with gain defined as DT fusion energy divided by the sum of the energy absorbed by the capsule and the ion beam energy. Not surprisingly, we find (as shown in the left panel of Fig. 2), that for a 375 MeV carbon beam with 10% energy spread, gain increases monotonically with beam energy.

In the right panel of Fig. 2, we examine the effect of varying beam energy while keeping fixed the total energy of the beam and beam duration. We consider three beam ion species: protons, C$^{6+}$, and V$^{23+}$, each with 10% energy spread and total ion beam energy 14.2 kJ. Gain is found to possess a maximum for a given energy. Further study of the burn evolution indicates that peak gain occurs for energies such that the two counter-propagating ignitor beams pass through one another at the origin. This leads to ignition of both the central region of the capsule and the hot spots outside the capsule. In the figure, an inflection is seen in all three curves associated with the location of the hot spot moving with increased beam energy from the dense region outside the core, to the less dense, hotter core, and finally to the dense region beyond the core. Interestingly, all three beam species give approximately the same maximum gain, however the higher the beam ion charge, the higher the energy per nucleon required and the lower the number of ions needed in the beam. The higher the Z, the higher the mass and the energy/nucleon needed. Going to higher-Z has the advantage that fewer ions are needed (which reduces the source surface area), but has the possible disadvantage of requiring much more ion energy, which can become impractical for a given short-pulse laser driver.

We show in Fig. 3 three sets of log plots of thermonuclear burn rate $R = n^2 \langle \sigma v \rangle_{DT}$ within the DT capsule for three different beams. The top row of panels shows burn evolution for a beam with ions of energy 375 ±37.5 MeV such that the hot spot is generated away from the center of the capsule. The central row of panels are for a beam of higher ion energy (500 ±50 MeV) but identical total beam energy such that the hot spot is located near the center of the capsule. (In this case, corresponding to the largest gain, as evinced in Fig. 2, the beams overlap one another at either side of the center of the capsule). The bottom panel is for a beam of ions with energy 750 ±75 MeV, where the ion beams pass through one another and create hot spots on the opposing sides of the center of the capsule. The highest gain is obtained when the ion beams are made to slightly overlap one another near the center of the capsule. In this case, one has a nearly symmetric burn front that propagates away from the center of the capsule.

We note that though methods such as the BOA can generate ions of the desired energy spread and energy/nucleon, it is an open question whether it is practical to use such methods for ion fast ignition, since this requires delivering several kJ of short pulse laser energy over an interval of hundreds of fs.
Figure 3. Thermonuclear burn rate $n^2 \langle \sigma v \rangle_{DT}$ within the DT fuel region for the capsule in Fig 1 ignited by a pair of counter-propagating carbon ion beams, each of energy 7.2 kJ. (Top row) Progression of TN burn initiated by a pair of $375 \pm 37.5$ MeV beams. (Center) Evolution of TN burn for a pair of $500 \pm 50$ MeV beams. (Bottom) Evolution of TN burn for a pair of $750 \pm 75$ MeV beams. In the center and bottom panels, the beams penetrate through the center of the target and overlap one another.

[1] Tabak Max, James Hammer, Michael E. Glinsky, William L. Krueer, Scott C. Wilks, John Woodworth, E. Michael Campbell, and Michael D. Perry, 1994 Phys. Plasmas 5, 1626.
[2] Maksimchuk, A., S. Gu, K. Flippo, D. Umstadter, and V. Y. Bychenkov, 2000 Phys. Rev. Lett. 84, 4108.
[3] Snavely, R. A., M. H. Keyh, S. P. Hatchett, T. E. Cowan, M. Roth, T. W. Phillips, M. A. Stoyer, E. A. Henry, T. C. Sangster, M. S. Singh et al. 2000 Phys. Rev. Lett. 85, 2945.
[4] Roth, M., T. E. Cowan, M. H. Key, S. P. Hatchett, C. Brown, W. Fountain, J. Johnson, D. M. Pennington, R. A. Snavely, S. C. Wilks, K. Yasuike, H. Ruhl, F. Pegoraro, S. V. Bulanov, E. M. Campbell, M. D. Perry, and H. Powell, 2001 Phys. Rev. Lett. 86, 436
[5] Atzeni, S., M. Temporal, and J. J. Honrubia, 2002 Nuclear Fusion 42, L1
[6] Temporal, M., J. J. Honrubia, and S. Atzeni, 2002 Phys. Plasmas 9, 3098
[7] Temporal, Mauro, 2006 Phys. Plasmas 13, 122704.
[8] Hegelich, B. M., B. Albright, I. Audebert, A. Blazevic, E. Brambrink, J. Cobble, T. Cowan, J. Fuchs et al., 2005 Phys. Plasmas 12 056314.
[9] Hegelich, B. M., B. J. Albright, J. Cobble, K. Flippo, S. Letzring, M. Paffett, H. Ruhl, J. Schreiber, R. K. Schulze, and J. C. Fernández, 2006 Nature 439, 441
[10] Albright, B. J., L. Yin, B. M. Hegelich, Kevin J. Bowers, T. J. T. Kwan, and J. C. Fernández, 2006 Phys. Rev. Lett. 97, 115002
[11] Robinson, A. P. L., A. R. Bell, and R. J. Kingham, 2006 Phys. Rev. Lett. 96, 035005.
[12] Yin, L., B. J. Albright, B. M. Hegelich, and J. C. Fernández, 2006 Laser Part. Beams 24, 291.
[13] Yin, L., B. J. Albright, B. M. Hegelich, K. J. Bowers, K. A. Flippo, T. J. T. Kwan, and J. C. Fernández, 2007 Phys. Plasmas 14, 056706.
[14] Zimmerman, G. B. and W. L. Krueer, 1975 Comments Plasma Phys. Controlled Fusion 2, 85.
[15] Lindl, John D., 1995 Phys. Plasmas 2, 3933.

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