Progress on Ion Based Fast Ignition

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Abstract. Research at Los Alamos on fusion fast ignition (FI) [1] initiated by laser-driven ion beams heavier than protons has produced encouraging results. The minimum requirements for FI are relatively well understood [2]. Based on simple considerations and on those requirements, it is shown that FI of the compressed DT fuel using laser-driven heavy ion beams has advantages compared to laser-driven proton or electron beams, along with different risks compared to those approaches. Using a technologically convenient light-ion species such as Carbon, ~ 100-fold fewer ions may deliver the energy necessary to ignite, simplifying target fabrication. Key requirements for success include the generation of a monoenergetic beam (energy spread ≤ ~ 10%), a sufficiently high ion kinetic energy (~ 450 MeV for C), and a sufficiently high conversion efficiency of laser to beam energy. An important benefit of this scheme is that such a high-energy, quasi-monoenergetic beam may be generated far from the capsule (~ 1 cm away), eliminating the need for a reentrant cone in the capsule, a tremendous practical benefit. This paper summarizes our progress in meeting those requirements, and the results of an integrated 2D design for a proof of principle FI experiment based on this concept.

1. Introduction
The minimum requirements for high fusion gain using the fast ignition (FI) approach [1] to inertial confinement fusion (ICF) are relatively well understood [2], and some are similar to conventional hot-spot ICF. The assembled fuel must satisfy certain requirements. In order to keep the amount of DT fuel and the yield at a manageable level, the fuel must be compressed to a mass density in the range ρ = 300–500 g/cc, which requires a high-quality capsule implosion. Achieving a high DT burn-up fraction for high efficiency requires an areal density ρr = 3 g/cm². In order to ignite the DT fuel, the FI particle beam must deposit at least $E_{FI} \sim 10$ kJ (the energy requirement) in a hot-spot volume with a linear dimension of ~ 25 μm (the volume requirement), within τ ~ 20 – 50 ps (the power requirement).

The FI power requirement makes particle beams driven by high energy, short pulse (~ps) lasers attractive. Such lasers can drive beams of electrons, protons or heavier ions, [3,4] all in principle suitable for FI [4,5]. (Hereon, “ion beam” includes protons, unless otherwise specified.) For a given conversion efficiency $\varepsilon$ of laser to particle energy, the energy requirement implies that the laser energy must be $E_L > E_{FI} / \varepsilon$. Such beams are born with a duration of order the laser pulse, but with a finite energy spread. When the beam is created close to the compressed fuel (e.g. with electrons), the power requirement is just a laser power requirement. For ions, the acceleration mechanism requires a short-pulse laser target that is distinct from the capsule, and whose integrity needs to be protected during the capsule implosion. In practice, this requires a short-pulse laser target placed away from the capsule. In that limit, for a given total beam energy, the power requirement and the ion energy spread result in
a tradeoff of distance & energy spread because the longer the beam drifts on its way to the fuel, the more it spreads in time, until the power requirement is not met - the fuel disassembles before it ignites. Therefore, the smaller the ion energy spread, the farther the ion source can be placed (with obvious target fabrication advantages) and the smaller the total beam energy can be.

The particle range has to be adjusted to the fuel per for maximum efficiency, which sets the ideal energy for the beam particle \( E_p \). For electrons, it is \( E_p \sim 1 \text{ MeV} \), for protons it is \( E_p \sim 13 \text{ MeV} \), while for C ions it is \( E_p \sim 440 \text{ MeV} \). The ion stopping is calculated using the code ISAAAC (Ion Stopping At Arbitrary Coupling) [6]. ISAAAC accounts for plasma effects, which yields significantly different results than stopping in cold matter. The beam particle energy is related to the laser intensity. Based on ponderomotive scaling [7], 1 MeV electrons requires \( I_L \sim 5 \times 10^{19} \text{ W/cm}^2 \). The TNSA process [8] requires \( \sim 10^{20} \text{ W/cm}^2 \) for 13 MeV protons. In the case of C, \( \sim 10^{21} \text{ W/cm}^2 \) is required (explained below). Finally, \( E_{\text{FI}} \) and \( E_p \) set the required number of beam particles, \( N_p \). \( N_p \sim 10^{14} \) for C and \( 10^{16} \) for protons. \( N_p \) is not a concern per se for electrons, but it can be for ions, as explained below.

2. Comparison of different ignitor-beam particles

An obvious candidate particle for FI is of course electrons, likely to feature the highest \( \varepsilon \). However, electron-based FI poses many challenges. Without a known way to focus FI electrons (in fact, it seems hard to avoid beam-spraying instabilities), maximum efficiency requires focusing the laser to the hot-spot linear dimension. Along with \( E_{\text{FI}} / \tau \), even assuming \( \varepsilon=1 \), such a beam size leads to an \( I_L \) higher than ideal. So, for a mildly optimistic \( \varepsilon \sim 1/2 \) and realistic electron transport, a laser energy significantly \( > \) than \( E_{\text{FI}} / \varepsilon \) is required, either because \( I_L \) and \( E_p \) are too high, or because the electron beam area is too large. A partial way out (if the electron beam is stable) may be to distribute the FI laser beams uniformly around the compressed capsule, which is technologically complex. An additional problem is the quasi-Maxwellian electron spectrum with \( \delta E_p / E_p \sim 1 \). As a result, the electrons range out over a distance larger than the desired hot spot dimension, leading to increased \( E_{\text{El}} \). Moreover, getting the FI laser beam through the coronal plasma to deposit near the core (to drive the electron beam) requires either a hole-boring laser prepulse, or a capsule with a reentrant cone [9], either of which presents significant difficulties.

Protons have different advantages and disadvantages. \( \varepsilon \) is lower than for electrons, increasing \( E_{\text{El}} \). However, ion beams can be ballistically focused to the hot-spot dimension [10], which decouples \( I_L \) from the hot spot dimension. Moreover, protons tend to range out over a smaller distance even when \( \delta E_p / E_p \sim 1 \), decreasing \( E_{\text{El}} \). However, until a mechanism for monoenergetic proton production is developed, TNSA yields a quasi-Maxwellian distribution with \( \delta E_p / E_p \sim 1 \). In practice, that requires placing the ion-beam laser target within \( \sim 4 \) mm from the capsule center, which requires a reentrant cone for protection. Moreover, \( E_{\text{FI}} / (\tau \varepsilon) \) and the ideal \( I_L \) set the ion-beam target area, \( \sim 1 \text{ mm}^2 \). Along with \( N_p \) the target area sets the proton source thickness, \( 2 \times 10^{18} \text{ protons/cm}^2 \). This is about \( 100 \times \) higher than adsorbed proton layers in typical target materials [3], and whether TNSA proton acceleration works with such thick layers remains to be demonstrated.

Laser-driven acceleration of heavier ions presents opportunities to sidestep the difficulties above. Heavier ions require higher energy per nucleon than protons in order to penetrate the compressed DT core. The higher energy per nucleon and the higher ion mass decreases \( N_p \) significantly. For C, a technologically convenient ion species, the required ion energy is estimated with ISAAAC applied to a simple geometry where the beam encounters DT fuel with an exponentially rising \( \rho \) (100 \( \mu \text{m} \) e-folding distance) up to a 25 \( \mu \text{m} \) long plateau of \( \rho = 400 \text{ g/cc} \). Initially, in order to range out in the plateau, \( \sim 40 \text{ MeV/nucleon} \) is initially required, with negligible losses in the preplasma. As the fuel heats up to \( \sim 1 \text{ keV} \), the required ion energy decreases to 9 MeV/nucleon, but 33 MeV/nucleon is lost in the preplasma. Generating a quasi-monoenergetic beam with such high beam energies is discussed in Sec. 3 below. The nearly monoenergetic \( (\delta E_p / E_p \sim 0.1) \) C beam could be generated far from the capsule (\( \sim 1 \text{ cm away} \)), eliminating the need for a reentrant cone in the capsule. Given \( E_p \), \( N_p \sim 10^{14} \) for C. In practice, one is likely to want a 50 nm thick C target, with a \( 10^{4} \text{ cm}^2 \) area.
The three key requirements for the success of this laser-driven low-Z ion-beam scheme include the generation of a sufficiently monoenergetic beam ($\delta E_p / E_p \sim 0.1$), with the required high ion kinetic energy, along with a sufficiently high $\varepsilon$.

3. Generation of the required ignitor-beam particles

The most promising candidate for producing the required ion beam parameters involve the so-called laser-breakout afterburner concept [11]. This concept was discovered with 1D & 2D simulations, with the powerful VPIC code, of a $\sim 10^{21}$ W/cm$^2$ laser beam with $\sim 30$ nm C targets, in some cases with typical levels of adsorbed hydrogen on the surface, which in fact do not make a difference in the accelerated C-ion parameters. Such thin targets require a very high laser-pulses contrast ratio ($> 10^{10}$), because too high a prepulse will launch a shock wave that will destroy the target before the peak of the pulses arrives. The acceleration mechanism consists of three phases: laser penetration across target, electron heating, and electron energy going into the ion energy via kinetic Buneman instability.

A limited number of massive simulations show the promise of the concept. 35% (in 1D) and 15% (in 2D) of all ions are accelerated to 0.3 GeV $\pm$ 7%, with 4% conversion efficiency for a Trident-scale laser. Moreover, C-ion acceleration is immune to surface proton contamination!

There is no existing short-pulse system where the afterburner concept may be tested. In order for us to do so, we are deploying a new laser front end on the LANL Trident with the required contrast. Pending further understanding, evaluation and optimization of candidate ion-acceleration mechanisms, the parameters of the ignitor laser system can only be estimated roughly: energy $\sim 100$ kJ, power $\sim 100-1,000$ PW, and laser intensity $\sim 10^{21}$ W/cm$^2$.

4. Integrated FI simulations with heavier ions

In order to test the concept in an integrated fashion, a proof of principle experiment has been modeled in 2D using the LASNEX hydrocode for the implosion and the beam-plasma interaction. These simulations are described in more detail in a separate article [12]. The first step is the fuel assembly, using a cryogenic DT capsule with a plastic ablator, with dimensions shown in Fig 1a. The capsule implosion was driven by a radiation source with a 14.2 ns pulse (foot + $P \sim t^{3.5}$ pulse) that peaks at 270 eV, as shown in Fig. 1B. The capsule absorbs 35.5 kJ. Peak fuel density is $\rho_{DT} \sim 150$ g/cc. This unoptimized capsule implosion shares a common feature, a high density shell with density depression in the center at peak compression.

This compressed capsule is used as a target for various ion beams, including protons and C. Motivated by the presence of the density depression at the core center, and the 2D nature of the integrated LASNEX simulation, two ignitor ion beams are injected along the symmetry axis, with an ion energy adjusted to range at different core radii. The x-ray emission during burn of an early FI calculation, showing the geometry of the ignitor beam injection, is shown in Fig. 2. In this early attempt, two (symmetric) C ignitor beams with ion energy ion energy $375 \pm 37.5$ MeV are used, each carrying a total beam energy of 7.2 kJ. The beams range out in the near side of the high-density shell, each producing an ignition spot $15\mu$m diameter and $10\mu$m long. The fusion gain relative to the ignitor beam is 2, i.e. the yield is $2 \times (35.5 + 14.4)$ kJ. At this ion-beam energy, the gain goes up approximately linearly with the total beam energy, reaching about 13.5 at $\sim 30$ kJ per ion beam.
Much better results can be obtained by adjusting the ion energy. Increasing the C-ion energy to 40 MeV/nucleon (480 MeV) with a similar % spread, while keeping the total 7.2 kJ/beam, results in a gain of 6.5. This is because a new burn mode is reached, i.e., each beam ranges out in the far side of the density shell. Interestingly, a beam (with the same energy) of 20 MeV protons, yields a gain of 6. FI of the same plasma with other ion species has been investigated, and found to yield similar results when the ion energy is adjusted to range in approximately the same location [11].

5. Summary
Based on published studies and simple considerations, it is found that fast ignition using ions heavier than protons may have considerable advantages over electron or proton FI, sidestepping many technological difficulties and offering a different set of risks relative to those other approaches. Achieving the required ion energies in a beam driven by a short pulse laser with sufficiently high laser-beam conversion efficiency is a challenge that is being undertaken by Los Alamos.

Such laser-driven ion beams, once demonstrated, represent an attractive alternative for FI. Integrated 2D simulations of integrated experiments at the proof of principle scale that could be fielded over the next few years have been done at LANL. The results indicate that significant gain would be achieved, justifying the step up to a larger, fusion energy-relevant test at the proof of performance scale.

6. Acknowledgements
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