Progress on the Development of Ion Based Fast Ignition

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Abstract. Results from research on fusion fast ignition (FI) initiated by laser-driven ion beams is encouraging so far. FI based on a beam of quasi-monoenergetic ions (protons or heavier ions) has the advantage of a more localized energy deposition, which minimizes the required total beam energy, bringing it close to the theoretical minimum of ≈ 10 kJ. High-current, laser-driven ion beams are excellent for this purpose, and because of their ultra-low transverse emittance, these beams can be focused to the required dimension, ~ 25 – 50 μm. Because they are created in ps timescales, these beams can deliver the power required to ignite the compressed D-T fuel, ~ 10 kJ / 50 ps. Our recent integrated calculations of ion-based FI include high fusion gain targets and a proof of principle experiment. That modeling indicates the concept is feasible, and provides confirmation of our understanding of the operative physical processes, a firmer foundation for the requirements, and a better understanding of the optimization trade space. Three four requirements for the success of this scheme include 1) the generation of a sufficiently monoenergetic ignitor ion beam (energy spread below ~ 10%), 2) with a sufficiently high ion kinetic energy (≈ 400 MeV for C), 3) along with a sufficiently high conversion efficiency of laser to beam energy, 4) and the ability to aim and focus the beam. This paper describes the theory and experimental progress in our research program, which is concentrated on fulfilling these requirements. An important benefit of the scheme is that such a high-energy, quasi-monoenergetic ignitor beam could be generated far from the capsule (≥ 1 cm away), so that the laser-target providing the beam may be protected from the implosion. If a beam made at that distance can be aimed, the need for a reentrant cone in the capsule is eliminated, a tremendous practical benefit. New schemes for laser-driven ion acceleration under experimental investigation at Los Alamos, the laser-breakout afterburner and radiation pressure acceleration, promise to deliver the necessary ion-beam performance. This paper summarizes the ion-based FI concept; the progress in developing a suitable ignitor ion beam, and the integrated ion-based FI modeling.

1. Introduction

The advent of high-power, high-energy short-pulse (~ps) lasers led to serious consideration of the concept of Fast Ignition [1]. In the FI variant of the Inertial Confinement Fusion (ICF) concept, such a laser delivers a sufficient power density to the DT fusion fuel (separately compressed) to ignite it, by isochorically heating a spot in the in the fuel to ~ 5-10 keV. The original concept envisioned that the hot electrons produced by the laser-fuel interaction [2,3] would be the actual ignition power source. Consideration of the difficulties in delivering the short-pulse laser to the overdense plasma led to the development of ICF capsules with reentrant cones [4], in order to keep a clear channel to the neighborhood of the compressed DT core. Experiments at the Nova PW laser demonstrated the efficient conversion of lasers to protons [5] via the Target Normal Sheath Acceleration (TNSA) mechanism [6], opening a whole new set of scientific possibilities on relativistic laser-plasma interactions, as well as practical possibilities to realize FI. A concept for FI with laser-driven proton beams soon followed [7], which has been refined further [8]. The idea is that the laser hits a target which is distinct from the

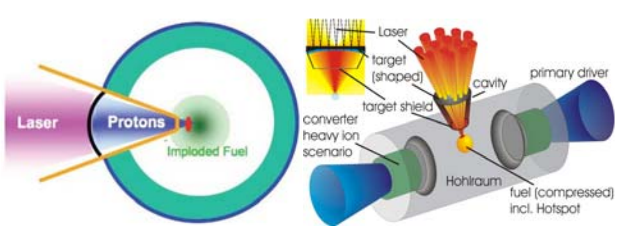

Fig. 1. Left: Proton-driven fast-ignition concept; Right: hohlraum-based proton FI concept [7].

fuel capsule. The laser power, transferred efficiently to the hot electron population, is extracted by the ion acceleration mechanism. The ion beam is focused on the fuel to ignite it. An important step on this concept is the demonstration of ballistic focusing of the laser-driven proton beam at the JanUSP laser (today part of the Jupiter facility) at LLNL, by proper shaping of the target [9]. Since then, laser-driven proton beams have been focused by electric fields in plasmas [10] at the LULI laser facility, and by miniature quadrupole lenses [11] at the LANL Trident laser and at the SNL Z-PW laser. Another encouraging element is the demonstration that laser-proton beam conversion efficiency and ion energy cutoff can significantly exceed published TNSA scaling laws [12] by using targets with advanced geometries [13], such as a hollow cone capped by a thin, small flat foil. Proton-driven FI remains a promising concept that deserves further exploration.

Another set of exciting possibilities was opened when using layered or microstructured targets led to the demonstration of laser-driven, quasi-monoenergetic C-ion beams [14] at the LANL Trident laser, and the demonstration of quasi-monoenergetic proton beams at the JETI laser in Jena, Germany [15], both still based on the TNSA mechanism. The key in realizing these results was the use of a thin layer of the desired species for the ion beam. These results and others [16, 17] on heavy ion acceleration have demonstrated the predictive capability of our modeling tools, including the atomic physics, which are severely tested in heavy-ion acceleration experiments. Inspired by the possibilities with thin target layers, the VPIC code [18] at LANL was used to carry out particle in cell (PIC) simulations, in 1, 2 and ultimately 3D, of high-intensity lasers on ultra-thin targets, i.e., tens of nm in thickness. The result was the discovery of a totally new acceleration mechanism, the laser Break-Out Afterburner (BOA) [19]. According to the latest simulations, BOA can be used to produce quasi-monoenergetic (energy spread $\delta E/E \sim 10\%$) laser-driven ion beams efficiently, with energies in the monoenergetic peak of ~ 1 GeV. In BOA, the laser transfers energy to the electrons, which sets a drift relative to the ions. The electrons transfer energy to the ions via a kinetic Buneman instability [20], with laser intensities as low as $I_L \sim 10^{20}$ -- 10^{21} W/cm^2 in sub-ps pulses. Recently, Radiation Pressure Acceleration (RPA), another mechanism promising quasi-monoenergetic ion acceleration (including protons) to ~ GeV energies, has been predicted to be effective at lower intensities (~10^{21} W/cm^2) than previously thought, provided electron heating is suppressed by using a circularly polarized laser beam [21]. The key to realizing either one of these schemes is the use of a very thin target, which in turn requires a laser with ultra high-contrast (~ 10^{10}), a level unavailable until now, to avoid the destruction of the target by the pre-pulse before the high-intensity peak arrives. A solution to this pulse-cleaning problem has just been implemented at the LANL Trident laser [22].

Quasi-monoenergetic laser-driven ion beams of a low-Z species like C (technologically convenient from the target fabrication point of view) offer great promise for FI, which has been examined recently [23, 24] using integrated simulations with the LASNEX hydrocode, using its ion beam package. The quasi-monoenergetic character of the beam enables very controlled energy deposition in the compressed core, and may allow the placement of ion-beam laser target, with its protective case, relatively far away (~ 1 cm) from the core, possibly eliminating the need for a reentrant cone in the capsule, greatly simplifying the implosion stage, if the beam can be focused and steered accurately. The high energy allows the ions to range in the desired areal density (ρr) of the core. Our studies of proof of principle (PoP) experiments with a conservative, low convergence capsule [24] indicate that, provided the ion energy is tuned correctly to the fuel ρr, ion beam species ranging from protons to mid-Z can ignite D-T fuel equally well (Sec. 3). Modeling indicates very high fusion gains (G~ 50—

100) when a C beam is tuned and focused to deliver the required power density to DT fuel compressed to conditions relevant to inertial fusion energy (IFE) [25].

It is well worth pursuing ion-driven FI (both with protons and higher-Z ions), as it is not assured that electron-driven FI is going to work, in spite of the successes in that research. Many areas of uncertainty remain, and a viable alternative is therefore important. When compared to electron-driven FI, ion-beam driven FI requires the extra energy penalty involved in electron-ion energy transfer. However, the separability of the ion generation from the compressed capsule, the possibility of focusing ion beams, the much more localized proton and ion energy deposition in the compressed fuel, and the stiffer ion transport, argue for ion-driven FI the preferred choice. Moreover, an ion beam is quite stiff compared to electrons - it is affected negligibly by the large magnetic and electric fields in the capsule corona.

2. Ignition requirements

The general requirements for ignition have been discussed (e.g. Ref. [26]), and may be estimated and understood from general considerations applying to any ICF concept [27]. The DT burn fraction depends on the fuel **areal density** ρr, and a reasonable burn fraction (> 10%) requires $\rho r \sim 1.5 - 3$ g/cm^2, which in turn sets the required energy for a given ion species. In order to heat the DT fuel in the hot spot to the required ~ 5—10 keV, faster than the heat conduction loss rate, a sufficiently high **power density** must be deposited by the ignitor particle beam. In order to produce a proper hot spot that initiates a propagating fusion burn, the power must be deposited over a volume ~ the range of a fusion 3.5 MeV alpha, which sets the total **ignitor particle-beam energy**. These requirements translate into a requirement ~ 10 kJ / 20 ps / [25 – 50 μm]^3 ~10^{22} W/cm^3. The required fuel **density** ($\rho \sim 300 - 500$ g/cm^3) is set by the desired fusion yield, which must be kept manageably small. The requirements for ignition are common to other ICF methods, and thus ion-driven FI benefits from the research on capsule compression in the broader FI and ICF community, using direct or indirect drive. The ion generation problem is separable from the implosion. (Hereupon, "ion beam" includes protons, unless otherwise specified.) Therefore, the generation of the laser-driven ion-beam FI driver is the present focus of our work. Our limited integrated target design work generates requirements for the ion ignitor beam, especially a C-ion beam, our prime candidate. Four requirements for the success of this scheme include 1) the generation of a sufficiently monoenergetic ignitor ion beam ($\delta E / E$ below ~ 10%), 2) with a sufficiently high ion kinetic energy ($E \sim 450$ MeV for C), 3) along with a sufficiently high conversion efficiency of laser to beam energy ($\varepsilon \sim 10\%$), 4) and the ability to aim and focus the beam. (Here ε is the conversion efficiency of laser to particle energy.)

Defining the conversion efficiency of laser to particle energy as ε, the ignition energy requirement of $E_{ig} \sim 10$ kJ implies that $\varepsilon \sim 10\%$ is necessary to keep the ignitor laser energy, $E_L = E_{FI} / \varepsilon$ at a manageable level of $E_L \sim 100$ kJ. Laser-driven ion beams are born within a period of order the laser pulse (τ), but with a finite energy spread δE. 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 versus energy spread, because the longer the beam drifts on its way to the fuel, the more it spreads in time, decreasing the power density it delivers. Therefore, the smaller the $\delta E / E$, the farther the ion source can be placed (with obvious target fabrication advantages), and the closer to the theoretical minimum the total beam energy can be.

The particle range must be adjusted to the fuel ρ*r* for maximum efficiency, which sets the ideal energy for the beam particle *E*. For electrons, it is $E \sim 1$ MeV, for protons it is $E \sim 13$ MeV, while for C ions it is $E \sim 440$ MeV (35 – 40 Mev/nucleon). Our most precise estimates on ion stopping are calculated using the code ISAAC (Ion Stopping At Arbitrary Coupling) [28]. ISAAC accounts for plasma effects, which yields significantly different results than stopping in cold matter. Nevertheless, and perhaps somewhat surprising, our integrated calculations using a more conventional modified Spitzer stopping model are not too far off in terms of the optimum *E*. For typical profiles expected in compressed capsules, and depending on the specific stopping model, we expect the ion beam to lose ~ 25% of the energy in the plasma on its way in towards the fuel core. In general, *E*.depends on I_L, with the exact value depending on the specific ion-generation mechanism. Finally, E_{ig} and *E* set the required number of beam particles, N_P. N_P is ~ 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. Ion beams can be focused to the hot-spot dimension, either ballistically [9,8], by shaping the laser focal spot (shape the I_L profile on the target), or conceivably by other means [10,11]. The ability to focus the beam decouples I_L from the hot spot dimension.

3. Comparison of different ignitor-beam particles

Protons have advantages and disadvantages compared to heavier ions. ε is lower than for electrons, increasing E_L. Proton beams have been ballistically focused to ~ the required hot-spot dimension [9,8]. Moreover, protons deliver energy much more sharply in space than electrons, even when $\delta E / E \sim 1$. However, monoenergetic proton production is not yet developed. TNSA yields a quasi-Maxwellian distribution with $\delta E / E \sim 1$, which requires placing the ion-beam laser target within ~ 4 mm from the capsule center, which requires a reentrant cone for protection of the proton-source. Moreover, $E_{ig} / (\tau\varepsilon)$ and the ideal I_L set the ion-beam target area, ~ 1 mm^2. Along with N_P the target area sets the proton source thickness, 2×10^{18} protons/cm^2. This is about 100× higher than adsorbed proton-rich contaminant layers in typical target materials [17]. TNSA proton acceleration with such thick layers is under development, and there is some encouraging recent progress [29].

The performance of heavier particles has been explored in a proof of principle experiment, modeled in 2D using the LASNEX hydrocode for the implosion and the beam-plasma interaction [24]. 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

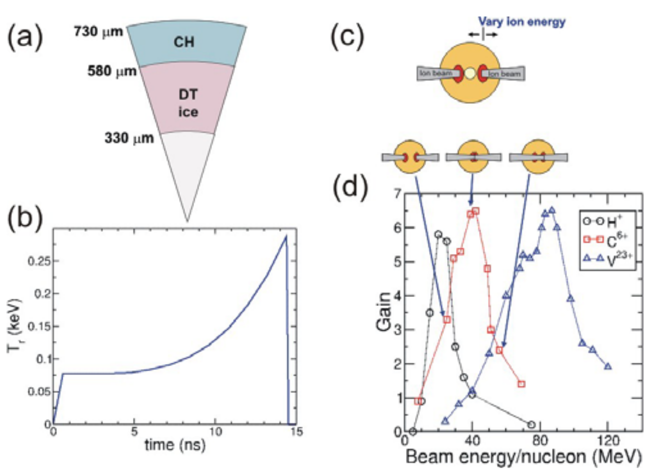

Fig. 2. (a) Capsule design for a possible PoP Expt.; (b) Implosion x-ray drive; (c) Geometry of the two ignitor beams in the 2D LASNEX simulation, propagating along the axis of symmetr;. (d) Fusion gain as a function of species and ion energy, for a total ignitor energy of 7.2 kJ × 2 [24].

eV, as shown in Fig. 2b. The capsule absorbs 35.5 kJ. Peak fuel density is ρ_{DT} ~ 150 g/cc. This capsule implosion shares a common feature, a high density shell with a density depression in the center at peak compression.

This compressed capsule is used as a target for various ion beams, including protons, C and V. 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 (Fig. 2c). The ion energy is adjusted, while keeping constant the total energy per beam (7.2 kJ/beam) and energy spread (10%). In all cases, provided that the beam energy is optimized, the fusion gain peaks at 6.5, which corresponds to the beam ranging around the same physical location. From these results, we conclude that provided that the ignitor particle delivers the required power density, any differences between ion species are second order, and other considerations (e.g., target fabrication technology) take precedence. Our choice of C is based precisely on that basis.

4. Performance of a C ignitor beam

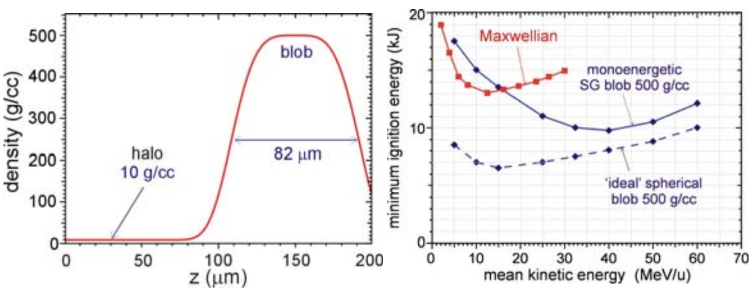

Fig. 3. Left: Idealized compressed DT fuel density profile; Right: Minimum beam energy for a C beam ($\delta E/E$ ~ 10%) to ignite the fuel [25].

A parameter scan of ion-beam FI has been done with the SARA design code [30], a hydrocode with multigroup radiation transport, fusion burn capabilities and an ion beam package with Monte Carlo transport. Figure 3, right, shows the minimum energy E_{ig} required to ignite the ideal fuel assembly (Fig. 3, left) with a supergaussian (SG) density profile and a peak density of 500 g/cm^3 when heated by a carbon ion beam born 650 µm from the dense core, with *δE/E ~ 10%*, and assumed to be focused to 31 µm in diameter. It is worth noting that ~10kJ of quasi-monoenergetic C ions can ignite the ideal fuel assembly. Further reductions of E_{ig} can be obtained by controlling the density profile of the surrounding plasma. The required E_{ig} increases modestly at larger beam-source to capsule separation.

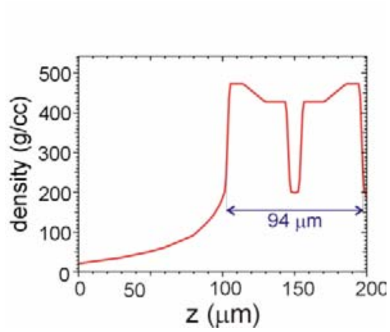

Fig. 4. DT density profile from a direct-drive implosion [32]

Ignition has been explored under more stringent conditions [31], with a C-beam generation point placed 2 cm from the capsule and a density profile from a self consistent direct-drive drive implosion design [32], shown in Fig. 4, which requires a laser energy of 485 kJ for the implosion. In Fig. 5, the minimum ignition energy is plotted for three different DT density profiles: Clark et al. (Ref. [32] & Fig. 4), idealized super Gaussian profile ("SG") in Fig. 3, left, and square

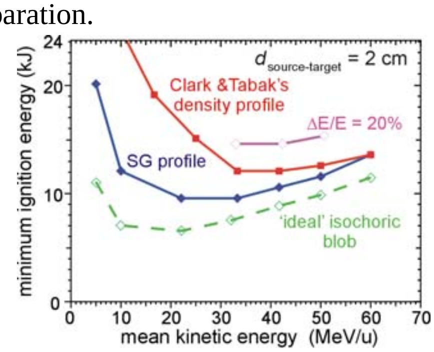

Fig. 5. Required E_{ig} for three fuel density profiles.

("water bag") - 100 μm in diameter, at 500 g/cc, with no coronal plasma. For lower kinetic energies, a significant fraction of the beam energy is deposited in the coronal plasma. The dependence of E_{ig} on E and $\delta E/E$ is analyzed in Fig. 5. We find that the C ignitor beam should have δE / E < 20% in order to keep E_{ig} manageable (below 15 kJ). It seems like a 12 kJ C ion beam with δE / E ~ 10%, and E ~ 35 MeV/nucleon is a reasonable point design.

5. Generation of the required ignitor-beam particles

BOA: A promising candidate for producing the required ion beam parameters is the so-called laser-breakout afterburner concept [19]. This concept was discovered with 1D & 2D simulations, with the powerful VPIC code [18]. The initial simulations utilized a linearly polarized laser at an intensity of 10^{21} W/cm^2, using ultrathin C targets (~ 30 nm) and pulse lengths of up to 231 ps. The general result is that after a brief period of target normal sheath acceleration (TNSA), two distinct stages follow: first, a period of enhanced TNSA during which the cold electron background converts entirely to hot electrons, and second, the "laser breakout afterburner" (BOA) when the laser penetrates to the rear of the target where a localized longitudinal electric field is generated with the location of the peak field co-moving with the ions. During this process, a relativistic electron beam is produced by the ponderomotive drive of the laser [2]. The electron distribution develops a net drift relative to the ion distribution. This beam is unstable to a relativistic Buneman instability, which rapidly converts the electron energy into ion energy [20]. This mechanism accelerates ions to much higher energies using laser intensities comparable to earlier TNSA experiments, and appears to dominate over acceleration due to charge separation fields. On the initial simulations the carbon ions accelerate as a quasi-monoenergetic bunch to 100 s of MeV in the early stages of the BOA with conversion efficiency of order a few percent. Both are an order of magnitude higher than those realized for quasi-monoenergetic C beams from TNSA in recent experiments [14]. The electrons eventually evolve into a quasi-thermal energy distribution with maximum energy of ~2 GeV.

The initial experiments to explore the BOA mechanism are just now underway, because the necessary technology is just being deployed. The necessary diamond-like carbon (DLC) targets in thicknesses of 5, 10, 30, 40, 50 and 60 nm have just recently been fabricated at the Ludwig Maximiliens University (LMU) in Munich by our colleagues Daniel Jung (LMU) and Vitaly Liechtenstein (Kurchatov Inst., Moscow). These 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. To date, the only alternative has been to use plasma mirrors, which are lossy (~ 50% reflection), and may degrade the laser wavefront. We have just developed a novel method to improve the laser-pulse contrast to ~ 10^{10}, and implemented it on an alternate laser front end on Trident [33]. On initial tests at Trident, 5 nm-thin targets have been successfully shot, i.e., the target survives the prepulse. In contrast, with the conventional Trident laser front end (~10^7 contrast) we can shoot successfully a 1 μm-thick target, but a 100 nm target does not survive the prepulse.

The effect of target contamination by H-rich impurities has been investigated. Furthermore, the typical thickness of these layers is much closer to the foil thickness in these BOA targets. VPIC simulations have been done with C targets with H contamination implemented in two ways: distinct H layers on the surface, and H entrained in the C foil. In either case, it is found that BOA C targets are self-cleaning, i.e., the protons are quickly accelerated pushed ahead and aside and the C acceleration proceeds pretty much as with a pure C target [19]. These protons, which roughly co-move ahead of the C-ion cloud, are therefore expected to be down in energy compared to the C, by roughly the ratio of the C/proton masses.

The results from preparatory experiments are encouraging. Experiments on Trident with dual plasma mirrors (~ 30 J on target) have made a C beam (not monoenergetic) with a high-energy cutoff of 180 MeV [34], probably in the enhanced TNSA regime. Recent Vulcan experiments with reduced-mass silicon-nitride targets appear to have accessed the enhanced TNSA regime also, with a significant ion population above 10 MeV/nucleon [35].

RPA: Another promising mechanism is radiation-pressure acceleration (RPA) [36], for which experiments are also just getting underway on Trident. To understand RPA, consider a high-contrast laser pulse incident on a target with a very steep density gradient. At the critical surface, there is a huge axial gradient of the laser transverse electric field E_0, and therefore the electrons are accelerated forward by the resulting ponderomotive force, $\propto \nabla(E_0)^2$. With linear polarization, the electron-laser interaction results in a Maxwellian electron energy distribution [2]. Simulations show that this ponderomotive (or $J \times B$) heating relates to the net forward acceleration of electron bunches, at twice the laser frequency, driven by an electrostatic field given by the oscillatory component of the ponderomotive force [2]. However, for a circularly polarized laser at normal incidence, there is a steady ponderomotive push, not heating, except that due to non 1D effects as the laser bores into the target. For a sufficiently strong push, the electron population can be displaced forward significantly, relative to the ions, and the corresponding strong charge separation field accelerates the ions. Continued laser irradiation keeps the process going. This acceleration mechanism is RPA, also know as the plasma piston [37]. Simulations in Ref. [36] of pure H laser targets illuminated at 10^{21} W/cm^2 indicate proton energies ~ 1 GeV. Similar values of ion energy/nucleon should be possible with laser targets with heavier species, or alternatively, ~GeV ion energies at lower laser intensities. In fact, for a given charge-separation electrostatic potential, RPA favors energy transfer to, and acceleration of, the more massive species. Therefore, as in BOA, we do not have to worry about proton contamination of our targets. RPA is possible with linearly polarized laser pulses, but only at much higher intensity [35]. Experiments to test RPA require a laser with circular polarization and minimal prepulse, both of which are only available on Trident at present. In order to realize RPA at a manageable laser energy and intensity, the electron population in an ultrathin target (~ 30 nm) must be displaced forward a distance equal to a significant fraction of the target thickness. High laser-pulse contrast is also required because prepulse drives gradients that complicate the realization of this charge separation.

A key to realizing RPA at Trident-like intensities lies in the use of circular polarization. This requires nearly normal incidence of the laser on the target. Otherwise, BOA dominates. Therefore, the target illumination must be optimized to remain quasi 1D, i.e., the target can only be driven until the longitudinal displacement of the plasma under the laser push becomes comparable to the focal spot transverse dimension. Our preliminary 3D VPIC simulations of RPA have confirmed that rule of thumb. The result is that significant optimization is necessary for given laser and target parameters. However, as long as the acceleration process remains 1D, there are simple models to describe the resulting ion acceleration [34]. Trident experiments are being designed to validate our modeling and understanding. Key questions to be answered include whether the theoretically very high laser conversion efficiency into fast ions can be realized, whether there are any thresholds (e.g., laser intensity) for the RPA process, and how does it scale with laser, plasma and target parameters.

6. Summary

Based on published studies and simple considerations, it is found that fast ignition using a laser-driven C ion beam has considerable promise. 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 at Los Alamos.

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