Fast Ignition by Intense Laser-Accelerated Proton Beams

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The concept of fast ignition with inertial confinement fusion (ICF) is a way to reduce the energy required for ignition and burn and to maximize the gain produced by a single implosion. Based on recent experimental findings at the PETAWATT laser at Lawrence Livermore National Laboratory, an intense proton beam to achieve fast ignition is proposed. It is produced by direct laser acceleration and focused onto the pellet from the rear side of an irradiated target and can be integrated into a hohlraum for indirect drive ICF.

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Energy production by inertial confinement fusion (ICF) has been a major field of thermonuclear research for over 20 years [1,2]. Two approaches are currently being investigated: direct drive [3] and indirect drive [4]. In direct drive ICF, high power lasers are used to irradiate the surface of a deuterium-tritium microsphere, to ablate the outer surface thereby compressing the inner part of the nuclear fuel. Precise temporal tailoring of the driving pulses must symmetrically compress and heat the fuel to form a hot spark in the center which drives a thermonuclear burn wave, which propagates through the pellet.

In indirect drive ICF, the fuel-containing pellet is placed inside a hohlraum, i.e., a radiation confinement cavity, whose interior walls are heated by lasers, ion beams, or by x rays from a Z-pinch plasma. The resulting soft x-ray radiation from the walls drives the implosion with a much higher degree of symmetry, but at the cost of an increased driver energy due to the limited conversion efficiency of the driver energy to soft x rays.

Fast ignition (FI) [5] was proposed as a means to increase the gain, reduce the driver energy, and relax the symmetry requirements for compression, primarily in direct-drive ICF. The concept is to precompress the cold fuel and subsequently to ignite it with a separate short-pulse high-intensity laser or particle (electron or ion) pulse. Fast ignition is being extensively studied by many groups worldwide [6]. There are several technical challenges for the success of laser-driven FI. Absorption of the ignitor pulse generates copious relativistic electrons, but it is not yet known whether these electrons will propagate as a stable beam into the compressed fuel to deposit their energy in a small volume. For indirect drive, the use of a laser ignitor is prohibited by the absorption of the laser light in the hohlraum wall and the ablation plasma.

In principle, heavy-ion beams can have advantages for FI. A focused heavy-ion beam may maintain an almost straight trajectory while traversing the coronal plasma and compressed target, and ions have an excellent coupling efficiency to the fuel and deliver their energy in a well defined volume due to the higher energy deposition at the end of their range (Bragg peak) [7]. However, a major problem for heavy-ion fast ignition is to achieve the necessary beam brightness (small spot size, short pulse length). Transport of the ion beam over a few meters inside a reactor chamber to reach the target will result in a larger than optimal beam spot size, which will require a higher than necessary ion pulse energy.

In this Letter, we present a new concept for FI which relies on an intense, short-pulse, laser-accelerated proton beam generated in close proximity to the compressed fuel pellet to provide the ignition spark. This concept was motivated by the recent observation of intense high energy proton beams in petawatt-laser [8] solid interactions [9,10], and it offers the promise of realizing the advantages of ion-driven FI while circumventing the difficulties of ion acceleration, pulse compression, focusing, and transport. Moreover, it can be applied to both direct drive and indirect drive ICF geometries.

Our concept for fast ignition using laser-accelerated protons is depicted in Fig. 1. Multiple petawatt-class laser beams are focused onto a target which is attached to the hohlraum in an indirect drive ICF geometry. An intense beam of protons is accelerated from the rear, nonirradiated surface of the target, which is spherical in shape in order to ballistically focus these protons to a small spot. For

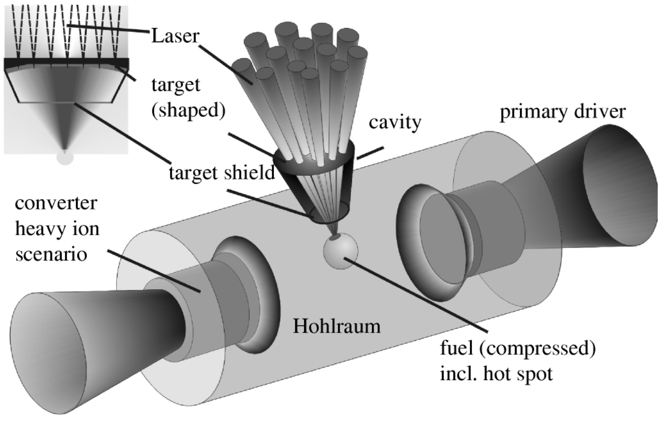

FIG. 1. Indirectly driven fast ignition using a laser accelerated proton beam (not to scale). The rear surface of the laser target is shaped to focus the ion beam into the spark volume.

specificity, in Fig. 1 we show a hohlraum heated by heavy-ion beams; however, this could equally well be applied to both laser-driven and Z-pinch-driven hohlraum designs. A thin metal window in the hohlraum wall protects the rear surface of the proton target from preheat caused by the intense soft x-ray radiation which is generated in the hohlraum by the implosion driver. A vacuum gap between the proton target and the protective window of $\sim 200\ \mu\text{m}$ is required to provide both a sufficient distance for the proton acceleration and a buffer against the hydrodynamic expansion of the hohlraum entry window due to the heat deposited in it.

Extremely high proton currents can be focused ballistically into the hot spot without space-charge driven defocusing, because the protons are accelerated as a plasma with an accompanying electron cloud which provides space-charge neutralization. Once the protons penetrate the thin metal window, we assume that their space charge will be neutralized by the plasma within the hohlraum, confirmation of which requires further beam transport calculations beyond the scope of this Letter. However, since the proton beam density is everywhere much lower than the hohlraum plasma density, this assumption appears reasonable and in the following analysis we consider proton beam defocusing effects from multiple scattering and emittance only.

Fast ignition with an ion beam requires that the focused proton beam be capable of heating a "hot spot" in an isochoric, precompressed fuel to the ignition temperature $kT \geq 10$ keV. We consider a fuel of density ρ_0 driven to temperature T by a pulse of protons having a focal spot size of r_0 and a range R. The range of the heating particles is chosen to be $R = \rho_0 r$ (g/cm^2) to match the α-particle range in the compressed fuel at ignition temperature. Extensive numerical 2D simulations by Atzeni [11] in the range $50 \leq \rho_0 \leq 3000$ g/cm^3 indicate that a minimum deposited energy is required, which scales as

$$E_{\min} = 140 \hat{\rho}^{-1.85}\ \text{kJ},$$

where $\hat{\rho}$ equals $\rho/100$ g/cm^3. Figure 2 presents the optimum parameters for a proton ignitor beam (pulse energy, duration, power, and beam radius) based on these simulations as a function of the precompressed fuel density. The optimum proton beam size is set equal to the range in the compressed fuel, and the maximum proton pulse duration is determined by the expansion time of the hot spot, given by the hot spot size divided by the sound speed, $\tau = r_0/c_s$.

Several groups have recently reported the generation of energetic protons and ions from the interaction of ultraintense lasers with solid targets [9,10,12,13]. One experiment, performed at the LLNL PETAWATT laser [9,10], has further demonstrated that ions can be accelerated in a very high quality beam from the rear, nonirradiated surface of a thin foil. This offers the prospect of shaping the target surface to ballistically focus the ions to a small, extremely high current density spot.

The ion acceleration mechanism is described in detail in [14]. Very briefly, thin gold and plastic foils (100 μm thick) were irradiated with 600 J, 0.5 ps pulses of 1 μm laser light, focused to 3×10^{20} W/cm^2. Relativistic electrons generated from the laser-plasma interaction, having an average temperature of ~ 7 MeV, envelope the target foil and form an electron plasma sheath on the rear, nonirradiated surface. The electric field in the sheath can reach $>10^{12}$ V/m, which field ionizes atoms on the surface and accelerates the ions very rapidly normal to the rear surface. Protons, having the largest charge to mass ratio, are preferentially accelerated in favor of heavier ions, and up to 10^{13} protons were observed in a highly directional beam, with an approximately Maxwellian energy distribution at $kT = 6$ MeV. The conversion efficiency of laser light to energetic protons was about 5%, with approximately 30 J of energy in the proton beam [10].

We suggest that laser-accelerated protons by the above mechanism can provide a more efficient and advantageous ignition source for FI than other scenarios previously considered. The laser-accelerated proton beam offers the principal advantage over conventional accelerator-based ion

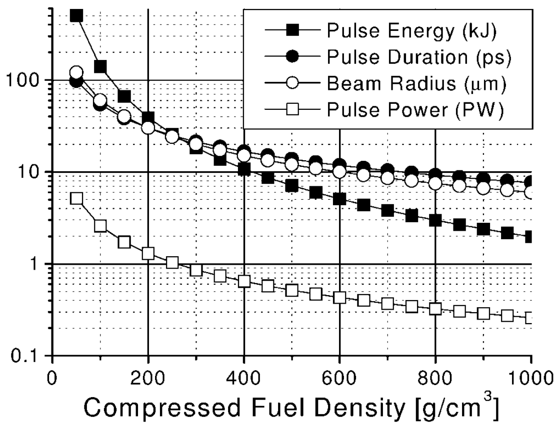

FIG. 2. Optimum parameter range for fast ignition based on 2D simulations by Atzeni.

beams in that the protons can be produced and accelerated very rapidly, up to tens of MeV in less than a few ps over a distance of less than 100 μm, and therefore may be generated very close to the fusion pellet. This avoids the severe problems associated with the focusing and transport of an accelerator-based beam through a reactor vessel to a precompressed fuel pellet. Experimental results, supported by particle in cell (PIC)-code simulations [14], indicate the possibility of focusing the proton beam by shaping the rear surface of the target (see upper left inset in Fig. 1). Furthermore, laser-accelerated proton beam FI does not depend on the choice of the hohlraum driver.

The energy deposition requirements for igniting a compressed fuel pellet described above limit the usable energy range for the laser-accelerated protons due to (a) the proton range in the compressed fuel and the intervening ablation plasma, (b) the temporal dispersion of the proton ignitor pulse, and (c) the energy-dependent emittance of the proton ignitor beam which determines its focusability. The usable fraction of the total number of protons produced then determines the required energy of the laser needed to produce the proton ignitor beam.

To analyze the range and energy deposition profile of the protons, we calculated their energy loss in the hohlraum wall (30 μm Au), the hohlraum plasma, the ablation corona and in the compressed fuel, taking into account the energy and angular intensity distribution of the beam. The required conditions of the hot spot are $\rho_0 r_0 = 0.6\ \mathrm{g/cm^2}$ at $kT = 10\text{–}12$ keV, and we choose as a working point a compressed fuel density of $\rho_0 = 300\ \mathrm{g/cm^3}$ (see Fig. 2). We consider a proton ignitor beam generated from a target placed 220 μm outside of the hohlraum wall. After penetrating the wall it traverses the hohlraum filled with plasma originating from wall blowoff and pellet blowoff and finally impinges on the compressed fuel producing the hot spot. As a first estimate, the energy loss was calculated in the framework of the standard stopping model [15]. For specificity, we have performed our calculations for a national ignition facility (NIF)-style target geometry.

For the proton transport calculation, we divided the distance from the source to the hot spot into 1 μm thick layers, for each of which the material and plasma parameters (taken from Lindl [16]) were determined. The electron density distribution close to the compressed fuel was chosen to rise from $0.1n_c$ (n_c = critical density at $\lambda_{\mathrm{laser}} = 350$ nm) to a fully ionized hydrogen plasma at $300\ \mathrm{g/cm^3}$ in agreement with [5]. The calculation of the energy deposition in the rest of the fuel assumed a constant density (isochorically compressed target). For each layer, the specific proton energy loss, and hence the associated energy deposition, was calculated for protons having initial energies between 5 and 35 MeV. The total energy deposited in a given layer was determined by convolving with a measured proton energy spectrum [10]. To include the energy dependence on the focusability, the measured beam emittance (see below) for each energy was used to calculate the respective spot size and therefore the fraction of the protons in the region of interest.

Figure 3 shows the calculated energy deposition profiles for protons having initial energies between 15 and 23 MeV (dashed curves). We find that protons within this energy range satisfy the first requirement for an ignitor beam, that they deposit the bulk of their energy (at the Bragg peak of their energy-loss profile) within the optimal $0.6\ \mathrm{g/cm^2}$ range in the compressed fuel. The solid curve in Fig. 3 shows the total energy deposition profile for protons in this optimal 15 to 23 MeV range, and Fig. 4 plots the fractional energy deposition along their path from the production target to the fuel. The typical energy loss penetrating the 30 μm gold hohlraum wall is about 1 MeV, and the energy loss in the hohlraum plasma is negligible compared to the fraction lost in the coronal plasma and finally in the compressed fuel.

The second constraint on the usable range of initial proton energies is the temporal dispersion of the ignitor proton pulse, whose total duration must be short compared to the expansion time of the hot spot. For our point design fuel density, the minimum hot spot size is the α-particle range required to sustain burn (20 μm), and the maximum allowable pulse duration is 20 ps (Fig. 2). The proton pulse duration is determined by both the intrinsic source duration and the temporal dispersion of the pulse due to the range of proton velocities and the path length from proton production target to the fuel. The acceleration mechanism (see [14]) provides an upper limit on the duration of the acceleration of $<$10 ps, due to the cooling time of the hot electrons in the plasma sheath which drives the proton expansion. In our example, the ignitor protons are generated 220 μm outside of the hohlraum wall and we assume a NIF-type hohlraum of diameter 5.5 mm. For protons between 15 and 23 MeV, the temporal spread of the proton pulse by velocity dispersion is $<$10 ps which, when convoluted with the intrinsic source duration, gives a total pulse duration of $<$20 ps.

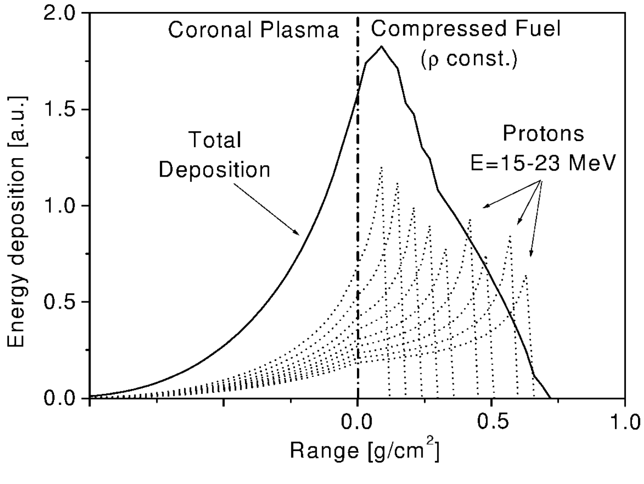

FIG. 3. Simulation of the energy deposition of protons in an isochorically compressed pellet.

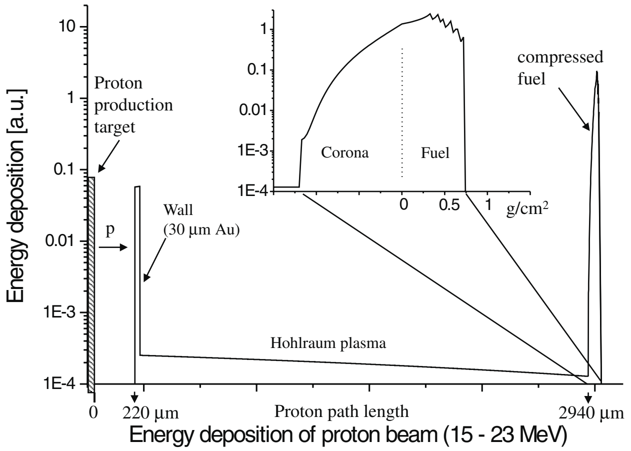

FIG. 4. Energy deposition of protons between 15 and 23 MeV in a NIF-type indirect drive target.

The final limit on the useful initial proton energy range is set by the proton beam emittance which determines its focusability. From direct measurements of core emittance of the proton beam generated in the PETAWATT experiments, we are able to set an upper limit on the normalized emittance of $\epsilon_N = \beta\gamma r_0 \theta_0 < 1\pi$ mm mrad for proton energies above 20 MeV. An analysis of the 2D electostatic plasma acceleration process suggests that the ultimate emittance of the beam depends directly on the temperature of the accelerated protons, and the experimental upper limit on is $kT \leq 5$ keV, but the data are consistent with a much colder beam. Calculations of the proton beam heating during the plasma expansion suggest temperatures of order 100 eV, which predicts a focal spot diameter based on emittance limitations only of order ≤ 20 μm for an ideal, ballistically focused proton ignitor beam from a shaped target.

Including straggling along the ignitor proton trajectories from the generation target to the compressed fuel, we predict an achievable beam spot of 25–30 μm diameter at the hot spot. We estimate that within this beam spot, the proton beam must deliver approximately 7–11 kJ, in a pulse duration of 13–16 ps. In a feasible FI scenario, the maximum laser energy for the FI ignitor beam should not exceed 100–200 kJ to satisfy gain and cost restrictions. Therefore an efficiency of about 10% laser light conversion into deposited proton energy must be achieved. The first PETAWATT experimental results achieved an efficiency of 2% for conversion of laser energy into protons between 15 to 23 MeV; however, this is strongly dependent on the energy spectrum of the emitted protons. According to theoretical considerations [9] the energy distribution is dependent on the plasma scale length on the back surface of the laser target and on the temperature of the hot electrons $T_{\mathrm{hot}} \sim (I\lambda^2)^{1/2}$. Therefore, by varying the laser intensity and the conditions on the rear surface of the target, the amount of protons in the desired energy range may be optimized to increase the overall efficiency.

The thickness and material of the shield in the hohlraum wall which protects the rear surface of the proton production target must be chosen thick enough to remain opaque for the x-ray radiation produced by the hohlraum driver (to avoid preheat of the ignitor proton target) and thin enough to minimize straggling of the ignitor proton beam penetrating the shield. The latter causes an increase of the spot size in the compressed fuel and consequently increases the required pulse energy. These conflicting requirements may be accommodated with a thin layer of high-Z x-ray absorber (e.g., Au) deposited on a mechanically stable low-Z support structure (e.g., beryllium or carbon) to minimize straggling.

In conclusion, the energy, intensity, and spatial structure of the intense proton beam recently observed in petawatt-laser irradiation of solids [10] make it a promising candidate for generating a ballistically focused, high-intensity proton pulse to trigger fast ignition. The pulse width and proton energy distribution are matched to the need of igniting a precompressed deuterium-tritium (DT) capsule. The measured intensity is sufficiently high to extrapolate this approach to future actual target conditions. Because of the dependence of the proton beam energy on the hot electron temperature, varying the laser intensity may increase the fraction of protons emitted in the desired energy range. The next generation of multikilojoule short-pulse lasers might then be able to achieve the required proton pulse energy for FI.

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