Fast ignition inertial fusion energy using laser-driven ion beams

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Executive Summary

Ion fast ignition (IFI), or fusion fast ignition initiated by a laser-driven ion beam, is a promising path to high-gain inertial fusion energy (IFE) [1,2]. In IFI, cold, dense deuterium-tritium (DT) fuel is first assembled using lasers or pulsed power drivers. Then, a high-power ion beam is focused onto a small volume within the fuel (the hot spot), heating the fuel rapidly to conditions where fusion ignition takes place. Fusion burn in this hot spot propagates to the fuel surrounding the hot spot, leading to burnup of a significant fraction of this fuel and the possibility of high gain (G~100), as needed for inertial fusion energy. IFI uses separate drivers for the two basic elements, fuel compression and ignition, allowing maximum control and optimization of each. On the other hand, conventional laser fusion uses multiple beams of the same driver to compress the fuel and shock-heat its very center to ignite a burn wave. Despite impressive progress in conventional laser fusion, the precise spatial symmetry, temporal pulse shaping and timing required for high gain and IFE remain a serious unmet challenge.

Profound advances in laser-ion acceleration and focusing over the last two decades and the compression of DT fuel to high density demonstrated on the National Ignition Facility (NIF) indicate the basic feasibility of the IFI concept. As a promising complementary approach, IFI is a worthwhile priority research direction because it provides an alternative path to success in IFE with a different risk profile than conventional laser-driven fusion. Yet it leverages and promotes the development of much of the same science and technology. However, further R&D investment is needed to address key technology gaps in IFI. Two different approaches for achieving ion fast ignition are apparent: the use of low-Z ions focused to the hot spot through a reentrant cone, and the use of high-Z ions generated externally to the capsule. Both have advantages and disadvantages that would need to be examined via development of point designs for fuel assembly and ignition, along with evaluation of various tradeoffs (e.g., laser-plasma instability (LPI) risk, efficiency, robustness). That examination would guide the definition of key gatekeeping metrics justifying further development, the required further development of central capabilities and the simultaneous experimental demonstration of key metrics.

Introduction

Ion fast ignition may be a viable path to high-gain inertial fusion energy production [1,2]. In order to achieve IFI, a mass of deuterium-tritium fuel is first assembled to high density (~500 g/cm^3) using traditional inertial confinement fusion (ICF) techniques such as laser-driven compression (directly or indirectly driven) or pulsed power drivers. Then, a high current ion beam, generated from the interaction of one or more high-intensity laser beams with converter targets, is directed toward a hot spot volume within the fuel in order to heat the hot spot fuel isochorically (i.e., without hydrodynamic

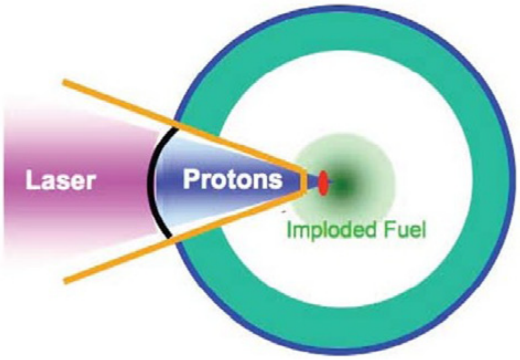

Fig. 1. Proton-driven fast ignition concept based on TNSA proton acceleration. (Reproduced from Ref. [3])

expansion) to a temperature of order 10 keV in order to ignite the fuel (see Fig. 1). Upon ignition, thermonuclear burn in the hot spot propagates into the surrounding fuel, leading to the potential for high fractional burnup (25% or more for high ρR DT fuel) and high gain.

In round numbers, an IFI ion beam must deliver a minimum power density of 10^{22} W/cm^3 to deposit 10 kJ of energy into a volume of linear dimension 20 µm (roughly the alpha-particle stopping range in the fuel, representing 0.5 g/cm^2 hot spot ρR) over a <20 ps time scale. Such rapid heating is needed to achieve ignition before the hot spot cools from hydrodynamic expansion, thermal conduction, and radiation. While conventional ion beams are precluded from achieving such high power densities by current and space-charge limits, laser-driven ion beams can do so because they're neutralized by co-moving electrons. Ion beams capable of igniting a hot spot appear to be feasible by scaling up present-day technology, though they have not been demonstrated at the currents and energies required for fast ignition.

For a given ρR of fuel, isochoric heating requires a higher temperature to achieve ignition (see Fig. 2) than traditional, isobaric approaches to thermonuclear fusion [4]. Though this may appear to be a disadvantage, in fast ignition, fuel compression and heating are *decoupled* from one another, providing an opportunity for optimizations that may not be possible with traditional approaches. For instance, to maximize robust, high-gain burn, high fuel ρR is desired to increase DT burnup fraction, given approximately by $\rho R/(6\ \mathrm{g{\cdot}cm^{-2}}+\rho R)$. Since the IFI hot spot is formed separately from the fuel assembly rather than jointly (where high ρR and high T in the hot spot work against one another), achieving high fuel ρR may be possible with more modest-scale drivers. The precise spatial symmetry, temporal pulse shaping, and timing required to generate an isobaric hot spot suitable for high burnup fraction with the same driver compressing the fuel to sufficiently high-density may be beyond the reach of existing capability. In IFI, however, the ignitor ion beam energy premium imposed by the isochoric hot spot is not a significant threat *per se* in the context of known issues with laser-driven ion beams. The modular nature of IFI supports independent maturation of the critical components of the technology (fuel assembly, ion beam generation and transport) before requiring investment in a facility that combines these capabilities, allowing for improved diagnostic access and more extensive risk mitigation.

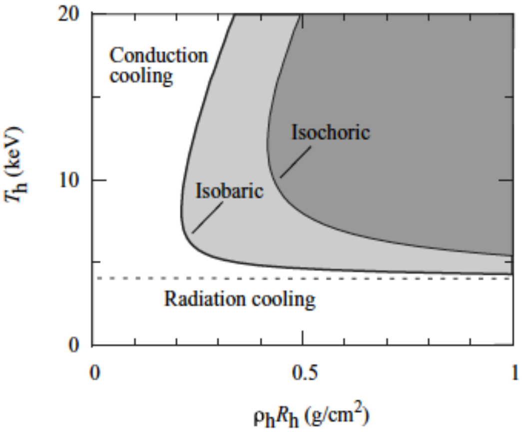

Fig. 2. Parameter space for a fusion hot spot within compressed DT fuel, according to an analytic model that balances alpha heat deposition and losses from PdV, thermal conduction, and radiation. (Reproduced from Ref. [4])

DT fuel assembly

In order to assemble the dense DT fuel, we can leverage advances in the inertial confinement fusion community, though the requirements for ion fast ignition fuel assemblies are somewhat different. Target density for IFI capsule target designs is around 500 g/cc and target ρR, as needed to achieve high gain, is 3-5 g/cm^2 (see Table 1). The requirement of high gain (~100) in an IFI power plant is likely to involve assembly of a large mass of fuel (450-2000 μg). It is unclear at this time what is the minimum size of the long-pulse laser driver for these assemblies. A high priority for an IFI program would be to undertake a design study to develop and, where possible, validate point designs for fuel assembly, considering a variety of options, including, e.g., wetted foam capsules which have been shown to have potential advantages for manufacturability and robust performance (low converence ratios, predictable performance) [5].

Efficient power delivery will be required. This will entail a high-fidelity, at-scale LPI study using high performance kinetic modeling codes [6] and consideration of techniques for reduction of nonlinear LPI losses [7] such as the use of enhanced bandwidth [8], color tuning (to control nonlinear CBET), and advanced beam conditioning techniques such as STUD pulses [9]. These techniques will be particularly important if longer wavelength laser drivers (more efficient but expected to be more susceptible to LPI effects) are considered. Also, it will be desirable to evaluate the use of directly driven capsules, which couple ~5x the laser energy to the capsule and have far simpler targets by avoiding the need for hohlraums.

Ion beam driver technology

Ion fast ignition is possible using a variety of different candidate beam ion species, which have advantages and tradeoffs. These options include low-Z species such as protons or deuterons and higher-Z species, such as carbon or aluminum ions. Presently, the largest technology gap for IFI lies between the existing state-of-the-art laser-generated beams (with ~few kJ short-pulse lasers, producing few-percent laser-to-ion efficiency) and those for IFI (~200 kJ in short pulse laser, assuming ≥5% conversion efficiency of laser energy into ions making it into the hot spot) A major challenge for this approach will be in scaling up the ion sources to the beam currents needed while maintaining the desired characteristics for IFI.

Low-Z ion beams: Generation of high-current, low-Z beams would most likely use target normal sheath acceleration (TNSA) from a converter laser target shaped to allow geometric “ballistic” focusing of the laminar ion beam. Beams with suitable proton energy and spectra have been demonstrated at a relevant (albeit still low) efficiency. Focusing has been demonstrated at existing high-power laser systems [10], albeit at reduced scale. TNSA is a mature technology that has been studied extensively for two decades. In order to reach the hot spot within the fuel without requiring prohibitively high ion-beam energies, a low-Z beam would require the use of a reentrant cone made of high-Z material such as gold (Fig. 2) within the fuel to shorten the propagation distance through the compressed fuel and guide the beam. Otherwise, the time-of-flight spread caused by the energy spectrum width decreases the power unacceptably. This complicates the hydrodynamics of fuel assembly, decreases main fuel burn efficiency (both by mixing of cone material into the fuel and by decreasing the fraction of solid angle occupied by DT fuel about the hot spot), and could lead to additional complications, as ablation and plasma filling of the cone could degrade the propagation of ions within the cone. The use of a cone geometry also complicates target fabrication and fielding, an important consideration for a facility intended to operate at high rep-rate (~10 Hz).

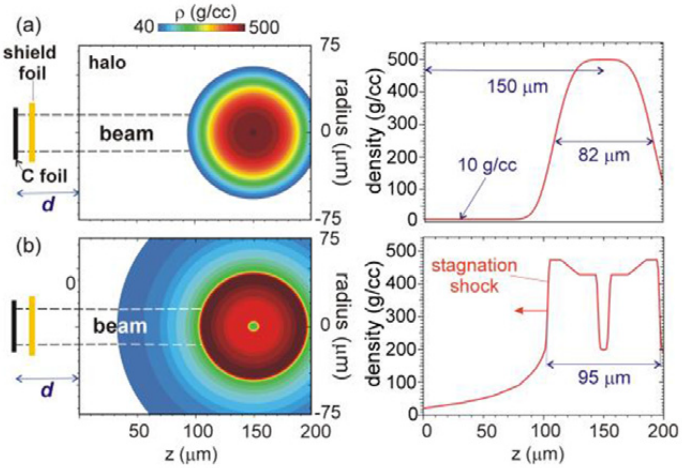

Fig. 3. Precompressed DT fuel density maps and profiles for two high-Z IFI cases examined in Ref. [11] (Reproduced from Ref. [11])

<u>High-Z ion beams</u>: Alternatively, a high-Z ion (e.g., C^{6+} or Al^{13+}) beam could be used, obviating the need for a cone (Fig. 3) because of their different stopping power within the DT fuel compared to protons. This huge potential advantage is offset by significant risks. Focusing of such ion beams remains to be demonstrated. The required ion energy spectrum and efficiency has only been approached simultaneously. Specifically, such high-Z ion beams would need to be generated with much higher mean energy and lower energy spread than in low-Z IFI concepts (e.g., C^{6+} ions of order 400 MeV central energy and 10% energy spread were considered in Ref. [2], compared with ~2-10 MeV proton ions). This requires the use of alternative acceleration mechanisms such as the break-out afterburner [12] or radiation pressure acceleration [13] that are less mature than TNSA, representing higher initial risk for an IFE program and necessitating an R&D effort to mature these ion beam acceleration technologies beyond the current state of the art. Several of these approaches also appear to require very thin (sub-µm-thick) laser targets, necessitating high pulse contrast, an additional complication for laser development, albeit one that has been demonstrated on multiple laser systems [14].

Though the development of high-Z and low-Z laser-ion sources has advanced dramatically over the past two decades, it is unclear whether complications will arise in scaling to the currents and energies necessary for IFI and whether it is possible to maintain simultaneously high efficiency and focusability. Scaling up the ignitor ion-beam energy may require driving a target with overlapping intense laser beams while preserving the quality of ion acceleration and focusability. This would therefore be a fruitful area of investment for an IFI program.

R&D Gaps

Several R&D or technology gaps would need to be addressed to realize the promise of IFI:

- Assembly of a cryo DT target to the required density and ρR
- Assembly of a cryo DT target to the required density and ρR for a capsule with a reentrant cone
- High efficiency rep-rated driver and short-pulse heater laser beam technology
- Assessment of laser-plasma instability risks in the driver and evaluation of efficacy of options for control and mitigatation of LPI in IFI drivers (e.g., green light, direct drive)
- Assessment of TNSA acceleration of protons or deuterons at high laser energy within cone geometry. Demonstration that the required efficiency and focusability can be maintained at the scale needed for IFI.

- Demonstration of necessary energy, energy spread, and focusability using advanced acceleration techniques for high-Z ions. The temperature of the co-moving electrons ultimately limit the focusability of the ion beam. Can we cool the electrons (e.g., with the use of transfer foils [15]) sufficiently for IFI?
- Evaluation of efficiency improvements to IFI ion beam generation – efficiency translates directly to smaller required energy in the short pulse driver and therefore target gain and other key fusion-reactor metrics.
- Robustness and reproducibility of IFI ion generation schemes
- High-power high-intensity lasers at progressively larger scales, as needed for IFI.
- Diagnostics for assessing performance of driver and ion heater beams.

Table of parameter space (design rep rate, gain, power output of plant)

The feasibility and desirability of IFI can be viewed in terms of possible IFE designs. The following are nominal values for prototype (Design 1), medium-scale (Design 2), and large (Design 3) IFI reactors. Each operates at 10 Hz and uses a 200kJ short pulse laser for ion beam generation. Nominal values have been assumed for electrical conversion efficiency (e), wall capture efficiency (b) [16], and driver efficiency (η). P_{grid} has been estimated using [2]

$$P_{grid} = \frac{P_{driver}}{\eta}\left(\frac{1}{p} - 1\right)$$

where $P_{driver} = (E_{shortpulse} + E_{longpulse}) * \text{Rep-rate}$ and the recirculating power fraction is $p=1/e\eta bG$. Obviously, improvements in driver efficiency, wall capture efficiency, and electrical conversion efficiency (common to all IFE approaches) would translate to increased reactor output for a given set of drivers.

	Design 1	Design 2	Design 3
Assembled fuel density (g/cc)	500	500	500
Assembled fuel radius R (μm)	60	80	100
ρR (g/cm^2)	3	4	5
DT fuel mass (μg)	450	1070	2090
$E_{shortpulse}$ (kJ)	200	200	200
$E_{longpulse}$ (kJ)	310	1240	3000
Yield (MJ)	51	145	320
Gain G	100	100	100
Rep-rate (Hz)	10	10	10
Electrical conv. efficiency e	0.4	0.4	0.4
Burn-up wall capture efficiency b	1.25	1.25	1.25
Driver efficiency η	0.1	0.1	0.1
P_{grid} (MW)	200	580	1300

Table 1: Nominal target capsule requirements for three different IFI high gain scenarios.

Design figures of merit and targets

- DT fuel assembly at $\geq$500 g/cc and ρR = 3-5 g/cm^2.

- Ion beam generation with >5% laser-to-ion conversion efficiency for focusable ions in the usable energy band (e.g., 400 MeV C ion beam with 10% energy spread for C^{6+} ion beams).
- Rep-rated high-energy short-pulse and long-pulse laser operation at ≥10 Hz with driver efficiency ≥10%.
- The energy of the long-pulse driver is relatively small relative to a conventional laser-fusion design, reflecting an advantage of only having to compress the fuel.
- The energy of the drivers have an obviously large lever arm in the design performance. These energies have a relatively high uncertainty rooted in the uncertainty in the underlying physics of fuel compression and focused ion-beam generation. Thus the impact on driver energy, especially short-pulse, may be an effective research prioritizing metric.

References

[1] M. Roth et al., *Phys. Rev. Lett*. 86, 436 (2001).

[2] J. C. Fernández et al., *Nucl. Fusion* 54, 054006 (2014).

[3] M. H. Key et al., *Fusion Sci. Technol*. 49, 440 (2006).

[4] S. Atzeni and J. Meyer-Ter-Vehn, *The Physics of Inertial Fusion* (Oxford; Oxford University Press; 2004).

[5] P. Norreys et al. Phil. Trans. R. Soc. A 379, 20200005 (2021); R. W. Paddock et al., Phil. Trans. R. Soc. A 379, 20200224 (2021).

[6] See, e.g., K. J. Bowers et al., Phys. Plasmas 15, 055703 (2008).

[7] L. Yin et al., Phys. Rev. Lett. **108**, 245004 (2012); L. Yin et al., Phys. Plasmas **26**, 082708 (2019).

[8] A. G. Seaton, L. Yin, R. K. Follett, B. J. Albright, and A. Le, "Theory and Simulation of Cross-Beam Energy Transfer Mitigation Through Increased Laser Bandwidth", submitted to Phys. Plasmas (2021).

[9] B. Afeyan and S. Hüller, Eur. Phys. J. 59, 05009 (2013); S. Hüller and B. Afeyan, Eur. Phys. J. 59, 05010 (2013).

[10] P. K. Patel et al., Phys. Rev. Lett. 92, 125004 (2003); T. Bartal, et al., Nature Physics 8, 139 (2012)

[11] J. J. Honrubia et al., *Phys. Plasmas* 16, 102701 (2009).

[12] L. Yin et al., *Lasers Par. Beams* 24, 291 (2006); L. Yin et al., *Phys. Plasmas.* 14, 056706 (2007)

[13] T. V. Liseikina et al., *Appl. Phys. Lett.* 91, 171502 (2007); O. Klimo et al., *Phys. Rev. ST Accel. Beams* 11, 031301 (2008); A. P. L. Robinson et al., *New. J. Phys.* 10, 013021 (2008); B. C. Liu et al., IEEE Trans. Plasma Sci. 36, 1854 (2008).

[14] R. Shah et al. *Opt. Lett.* 34, 2273 (2009).

[15] C.K. Huang et al. *Phys. Plasmas* 18, 056707 (2011); C.K. Huang et al. *Phys. Rev. ST Accel. Beams* 14, 031301 (2011).

[16] L. J. Perkins, "And Now on to Higher Gains: Physics Platforms and Minimum Requirements for Inertial Fusion Energy," Nov. 16, 2021, LLNL-PRES-828699.