Short Pulse Laser based Ion Fast Ignition for IFE

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Executive Summary

The historic near-breakeven laser fusion milestone obtained at the NIF in August of 2021 indicates that laser fusion could be a viable route to fusion energy. However, since the indirect drive method used in this first demonstration of near-breakeven is relatively inefficient, it is important to pursue alternative methods capable of achieving high gains as potential engines for an Inertial Fusion Energy (IFE) power plant if laser fusion is to become competitive with other alternative energy sources. One promising approach to achieving high gain is to consider the possibility of separating the compression and ignition stages in the process. In particular, using short pulse lasers to create an intense burst of electrons to ignite an isochorically compressed DT target ("Fast Ignition"[**1,2**]) has been investigated at low funding levels for 30 years. While significant progress along this research direction has been made recently in the US and Japan[**3**], another promising scheme introduced several years later, known as proton fast ignition[**4**], based on protons produced by the TNSA method of energetic proton production[**5**], has received considerably less attention. In this white paper, we propose an integrated theoretical/simulation/experimental program to study in detail the properties of laser-based ion fusion (including proton) as the engine for an IFE plant in light of three recent developments in the field: superponderomotive electron acceleration, high average power Petawatt class lasers, and ion wave-based plasma optics.

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Introduction

There are three requirements for proton ignition to achieve ignition conditions; i) proton energy spectrum 3-15 MeV to heat the fuel through areal density of 0.5 g/cm^2, ii) proton focusing to smaller than 50 micron spot size, and iii) creating laser pulses capable of creating the total amount of beam energy required (~ 10-20 kJ) given the small laser to proton conversion efficiencies thus far observed which are < 10%. Modeling and experimental work has been recently been published showing that it is possible to achieve some of these conditions[**6**].

Three recent developments that make this an exceptionally opportune time to revisit the short pulse laser generated ion approach to fast ignition. First, Mariscal et al.[**7**] has shown that the 1-10 ps wide spot, long f number laser pulses on the NIF ARC can produce proton energies and fluxes far in excess of estimates based on ponderomotive scaling, as a result of the generation of a large population of superponderomotive electrons[**8**]. This demonstrated the ability to deliver large amounts of energy by using large spots, yet still achieve intensities required to generate the requisite hot electrons to accelerate protons[**9**]. This resulting proton or ion beam would then be focused and injected into a pre-compressed DT core. The focusing of the proton beam through conical structures have been demonstrated by Bartal et al [**10**] and McGuffey et al. [**11**] showing the beam could be focused to smaller than 50 μm spot satisfying one of the requirements for proton PI, albeit at much lower currents than ignition scale beams.

Second, a beam combiner method that relies on ion waves to combine several ns laser pulses into a single beam[**12**] has achieved a record 8 kJ into a 1 ns pulse by combing 20 NIF beams into 1 beam. Scaling these current results up, by combining even more beams and then employing a Brillouin amplifier to convert the majority of this laser light to a short laser pulse, suggest the possibility of producing a ~60 kJ, 10 ps beam[**13**]. A TNSA target would then convert this laser beam to 6 kJ of protons with an exponential energy spectrum falling monotonically with energy between 1 and 25 MeV, which is the energy range required so the protons can pass through the coronal plasma and deposit in the compressed fuel[**14**]. This alleviates a major criticism of proton acceleration: namely, that laser beams will never reach the total energy required to make proton fast ignition competitive with other fast ignition approaches.

Finally, and perhaps most importantly, there are now laser architectures currently being developed that promise orders of magnitude higher average power than is currently achievable in high peak power (petawatt class) lasers. This limitation had been a fundamental roadblock in virtually all fast ignition schemes proposed, but this advancement in high average power now allows for reasonable IFE power plant cost estimates. In particular, it is projected that Tm:YLF [**15**] will be likely be capable of sustaining 300 kW average power, which is a 3 orders of magnitude increase compared to the current Petawatt lasers. This plan leverages ongoing work in this field.

Key Metrics

It has been estimated that if somewhere around 15kJ - 50kJ of kinetic energy in particles with the proper energy were deposited into a volume of DT compressed to somewhere around 300-600 g/cc, a self-sustained nuclear burn would be initiated and gains greatly exceeding unity would be realized[**14**]. The original Fast Ignition scheme relied on electrons at around 1 MeV energies. However, the directionality and scattering and lack of a localized deposition region made this approach technically difficult and research in the field all but evaporated. Proton or ion fast ignition (shown in Fig. 1(a)) has the advantage that (1) the protons can be produced far from the implosion, (2) can be focused, (3) are heavy enough to act ballistic through the coronal plasma surrounding the compressed core, and (4) have a distinct Bragg peak by which they can deposit their energy into the core (Fig. 1 (b).)

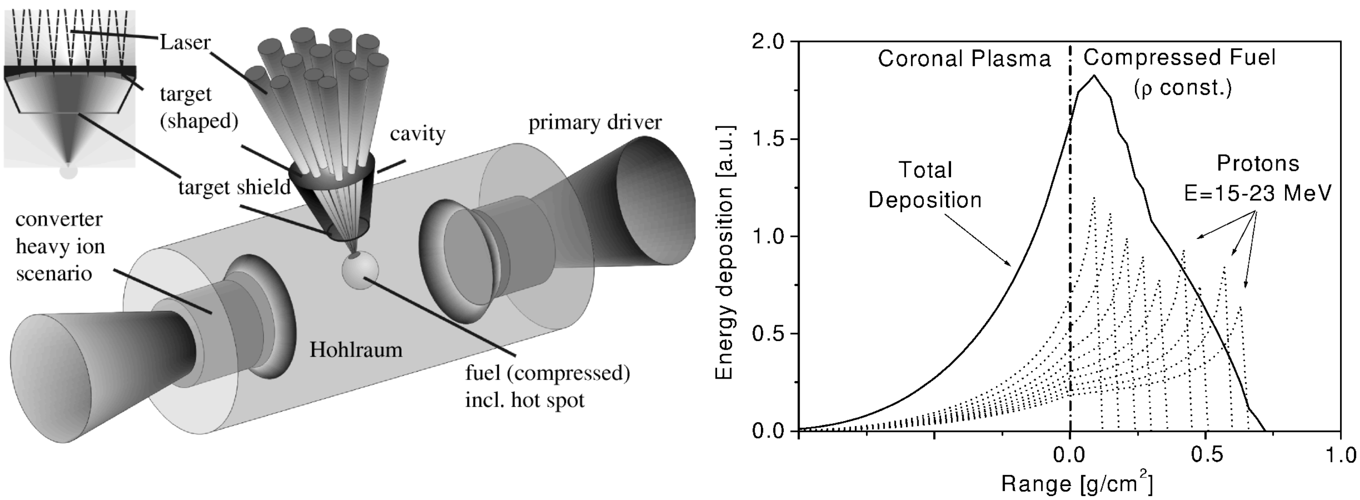

Fig. 1 (a) Schematic of a proton fast ignition implementation, where the fuel compression is driven by heavy ions, and not lasers. (b) Example energy deposition of a TNSA produced proton beam as a function of range into the compressed DT fuel. (From Roth et al. (2001))

To date, a record 8 kJ of laser energy has been put into a 1 ns pulse using the beam comber. Scaling the current results up, by combining even more beams and assuming a slight increase in efficiency, it may be possible to scale this up to 120 kJ. If this "Megabeam" is now used as the pump in a Brillouin Amplifier scheme where a 10 ps beam is amplified and the 120 kJ beam transfers 50% of this to the seed beam, this would result in ~60 kJ, into a 10 ps beam. Assuming a 10% efficiency into ions[**16**], this would result in 6 kJ. With just two of these Megabeams, it is possible to approach the required total particle energy to ignite a 600 g/cm^3 compressed fuel of DT[**14**].

Theory/Simulation Program

Prior modeling efforts on ion fast ignition can be found in both Fernandez et al. [**6,17**]. In order to make further progress in assessing the viability of ion ignition, a program consisting of a theoretical/simulation component and a parallel experimental component will be required. The experimental effort will be used to benchmark the laser and target parameters obtained via modeling. These parameters can then be fed into a model for an IFE plant.

The theoretical/simulation-based program will:

1. Determine optimal compression schemes that minimize the required laser energy.
2. Determine the best short pulse laser parameters for optimal ion generation.
3. Determine the best ion species and corresponding energies for ignition.
4. Support small scale ion acceleration experimental target design and analysis.

While the compression (implosion) phase will require radiation hydrodyamics codes [**18**], the short pulse ion acceleration physics studies will require substantial computational effort using kinetic codes. Hybrid PIC codes such as Chicago[**19**] and explicit PIC codes such as WarpX[**20,21**] will be employed in the studies listed above.

The experimental program will complement the above program in that it will:

1. Study proton acceleration and conversion efficiency in the TNSA regime for various laser pulse shapes/duration.
2. Test novel target designs, including various ion species, rep rated targets and diagnostics.
3. Carry out transport and focusing experiments with a high current TNSA beams.
4. Determine the achievable energies and subsequent stopping of TNSA proton/ion beams.
5. Explore novel methods of beam combining and amplification to create 100 kJ, 10 ps laser pulses

Experimental Program

NIF is the ideal place to continue the required beam combiner and Brillouin Amplifier research. This work will help determine the feasibility of obtaining the required short laser pulses capable of reaching greater than 100 kJ energies. However, the number of NIF shots at this scale is severely limited, and extensive studies to study the underlying physics behind ion acceleration and transport relevant to ion fast ignition would not be realized if restricted to just this scale. Therefore, concurrent with these activities associated with achieving a single laser pulse that is capability of generating the appropriate number and energy of protons (which is critical in demonstrating the feasibility of many advanced high gain ignition schemes) it is also advantageous to carry out the work at a high repetition rate at a smaller scale.

The LBNL laser facility is ideal for carrying out high repetition rate laser experiments to study proton acceleration and conversion efficiency in the TNSA regime for various laser pulse shapesand duration due to the 1 Hz repetition rate of the BELLA PW laser. Specifically, we propose to study in experiments at the BELLA iP2 laser facility the generation of protons with kinetic energies of 5-15 MeV in the TNSA regime at high laser to proton energy conversion efficiency.

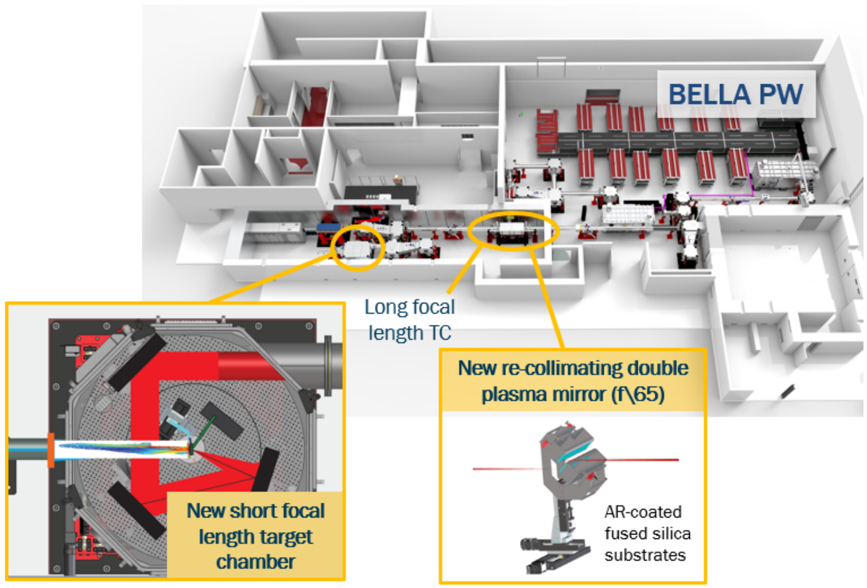

Fig. 2: Layout of BELLA PW beamline and the iP2 chamber**.**

The new iP2 facility at the BELLA PW will be commissioned in early 2022 and will deliver 40 J pulses with 35 fs pulse length. Figure 2 shows the layout of the BELLA PW laser and the experimental cave housing two target chambers. After pulse compression, the laser is focused with a long focal length (F/65) off-axis paraboloid (OAP) into the plasma chamber for electron and ion acceleration studies with a large focal spot. Previous experimental and simulation studies of laser-ion acceleration in the TNSA regime was recently completed with the long focal length OAP, where it was found that an increased laser spot size leads to sheath field geometries with a high aspect ratio of the laser spot size to the acceleration distance [**22,23**]. In this configuration, ion beams were accelerated up to 8 MeV with narrow and achromatic divergence at unprecedented charge densities. In a radiation biology experiment, these proton beams were used to uniformly irradiate 1 cm diameter biological cell monolayers to study the effect of ultra-high instantaneous proton dose rates on normal and tumor cell survival [**24**]. Significantly higher survival of normal versus tumor cells was observed consistent with reports on the so-called FLASH radiotherapy effect [**25**].

The new iP2 beamline is an extension to the existing laser beamline, where a second F/65 OAP is used to re-collimate the beam before it enters the iP2 target chamber. There, final focusing with the F/2.5 short focal length OAP results in peak intensities approaching 10^{22} W/cm^2. An on-demand double plasma mirror (DPM) assembly will be available to be inserted into the beamline in the plasma1 chamber for temporal contrast cleaning. These new experimental capabilities allow for ultra-high intensity laser-ion acceleration experiments in the TNSA regime, reaching ion energies of several 10 MeV per nucleon and shot rates that allow for large parameter scans at statistical relevance. More details on the experimental program at the BELLA PW are presented in the companion white paper "BELLA PW 1 Hz Laser Experiments for Short Pulse Laser-Based Ion Fast Ignition for IFE"[**26**].

Conclusion

We have outlined an integrated theoretical/simulation/experimental program that is formulated to determine the viability of a particular approach to fast ignition fusion, based on laser-generated protons or ions, for use as the energy source in an IFE power plant, based on a target physics and design perspective. Specifically, advanced simulation tools, informed by experiments that can be carried out on existing facilities, will be used to determine plausible IFE-relevant target design parameters. The outcome of this program will be a qualitatively improved understanding of the major target physics issues that are required to make the ion fast ignition approach to IFE a reality.

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