BELLA PW 1 Hz Laser Experiments for Short Pulse Laser-based Ion Fast Ignition for IFE

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Feb 14, 2022

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 method of achieving high gain is to consider the possibility of separating the compression and ignition stages in the method. 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 Japan [**3**], another promising scheme introduced several years later, known as proton fast ignition [**4**], based on protons produced by the target normal sheath acceleration (TNSA) method of energetic proton production [**5**], has received considerably less attention. In this white paper, we focus on the experimental program carried out at the BELLA PW, 1 Hz laser to investigate TNSA at high laser to ion energy conversion efficiency and to validate simulations and theoretical concepts that are relevant for proton fast ignition.

Introduction

There have been three recent developments that make this an exceptionally opportune time to revisit the short pulse laser generated ion approach to fast ignition; first, the generation of high energy, high flux laser-accelerated proton beams at NIF ARC [**6**] that could be focused and injected into a pre-compressed DT core, second, a laser beam combiner method that has achieved record 8 kJ in a 1 ns pulse [**7**], which could be extended with the necessary components to produce a ~60 kJ, 10 ps beam [**8**]. 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 [**9**]. This alleviates a major criticism of proton acceleration for IFE: namely, that laser beams will never reach the total energy required to make proton fast ignition competitive with other fast ignition ideas. Third, 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. Since this limitation was a fundamental roadblock in virtually all fast ignition schemes proposed, this advancement now allows for reasonable IFE power plant estimates. In particular, it is projected that Tm:YLF [**10**] will 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.

We propose to study in experiments at the 1 Hz BELLA PW the generation of protons with kinetic energy of 5-15 MeV in the TNSA regime at high laser to proton energy conversion efficiency. These optimized proton beams will be used to study the isochoric heating of few mm diameter solid samples to reach warm dense matter (WDM) states that are relevant to IFE and to investigate proton transport and stopping in already heated WDM samples. This experimental program is part of a concerted effort with a theory/simulation program described in the separate white paper "Short Pulse Laser based Ion Fast Ignition for IFE" by Scott Wilks et al [**11**].

The BELLA PW delivers 40 J, 35 fs laser pulses at 1 Hz repetition rate, which are suitable to study the described phenomena in large parameters scans at statistical relevance. To reach high particle numbers and, hence, high laser to proton conversion efficiency in the proton energy range of interest of 5-15 MeV, it is desirable to reach significantly higher cutoff energies around 40-50 MeV to benefit from the exponential shape of the energy spectrum. This regime is accessible with the new BELLA iP2 short focal length off axis paraboloid setup, delivering laser intensities approaching 10^{22} W/cm^2 to the target (see Fig. 1).

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 1 would be realized [**9**]. Proton or ion fast ignition 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 where they can deposit their energy into the core.

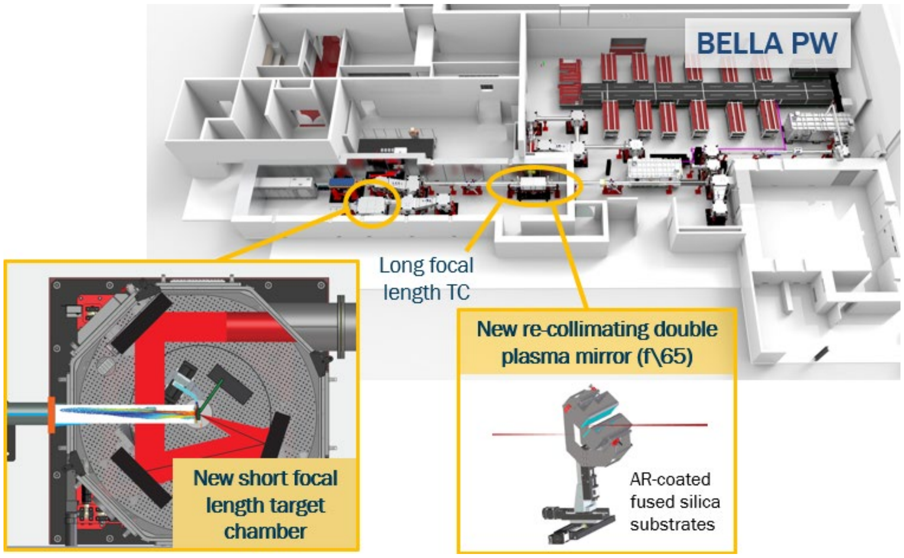

Figure 1: Layout of BELLA PW beamline and the iP2 chamber with the short focal length OAP.

Generating a 60 kJ 10 ps laser pulse to efficiently accelerate the required proton and ion beams via TNSA may be feasible through laser beam combining. Assuming a 10% efficiency into ions [**12,13**] this would result in a 6 kJ ion pulse. 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 [**9**].

The proposed research will be executed in the form of a theory/simulation program and an experimental program. The theory/simulation program is described in [**11**]. The experimental program will:

1. Study proton and heavier ion acceleration and conversion efficiency in the TNSA regime for various laser pulse shapes/durations.
2. Test novel target and diagnostic designs, including those suitable for high repetition rates.
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 120 kJ, 10 ps laser pulses.

Items 1-4 will be executed at the 1 Hz BELLA PW laser at LBNL. Item 5 will be executed at LLNL. This white paper describes the experimental program executed at the BELLA PW laser.

Experimental Program at the 1 Hz BELLA PW laser

The proposed experimental studies will be possible with the new iP2 target area of the BELLA PW laser at LBNL, delivering 40 J pulses with 35 fs pulse length (Fig. 1). The 1 Hz BELLA PW laser [**14**] has been operational since its commissioning in 2013 and has been used for laser wakefield acceleration of up to 8 GeV electrons [**15**] and TNSA of up to 8 MeV protons [**16**] (Fig. 2). The new iP2 beamline features a short focal length (F/2.5) off-axis paraboloid (OAP), designed to enable a few µm diameter focal spot with intensities approaching 10^{22} W/cm^2 and an on-demand double plasma mirror (DPM) to suppress uncontrolled pre-pulses and pulse pedestals and prevent early target expansion. Apart from the DPM, more pulse shaping capabilities are available to vary the pulse length and to generate more complicated pulse shapes. A tape drive assembly for the

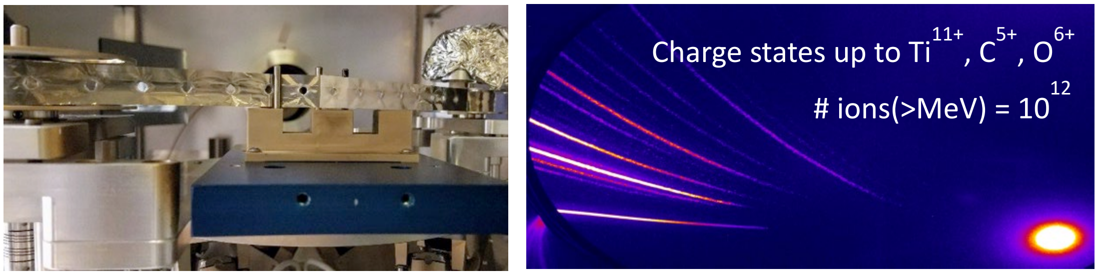

Figure 2: Ion acceleration using a titanium tape drive target the BELLA PW (left) and ion traces detected with a Thomson parabola spectrometer for peak intensity on target of $1.2x10^{19}$ (right). Apart from protons, heavier ions originating in the hydrocarbon contamination layer and the target bulk are detected, such as carbon, oxygen and titanium ions.

rapid insertion of ~10 µm thick plastic targets at 1 Hz is already available for experiments at iP2 (Fig. 2, left side).

Advanced target designs: We will field advanced target designs to improve laser to proton energy conversion efficiency in TNSA, primarily by improving laser energy absorption into the plasma electrons. Microstructured targets, such as those involving low-density layers attached to the target front like foams [**17**] or microtubes [**18**], have been used to improve laser absorption by effectively increasing the number of electrons interacting with the laser field. Another scheme involves microcones to benefit from grazing laser incidence and thus increased electron heating [**19,20**]. Mass-limited targets with lateral dimensions not much bigger than the focal spot were fielded to increase electron heating by limiting the lateral extent of the electron sheath as it recirculates through the target [**21**]. With simple large flat foil targets, tailoring the preplasma density profile at the target front by changing temporal contrast conditions has shown increased absorption as well [**22**]. Apart from improving laser absorption into the target electrons, structured targets were used to reduce the energy spread of the generated ion beams by attaching microdots to the rear surface of a foil target [**23**].

High repetition rate capability: An important challenge is to find a suitable target to improve laser to ion energy conversion, while at the same time answering the need for high repetition rate (HRR) capability. HRR experimental operation requires rapid target and, if using the DPM, plasma mirror formation and alignment technology, as well as active diagnostics that can match the laser pulse repetition rate of 1 Hz. Also, the experimental assembly needs to withstand potentially very large electro-magnetic pulses originating in the laser-plasma interaction. Another concern is the mitigation of debris that can harm the surrounding components. Apart from the tape drive [**24**] routinely used at the BELLA PW, promising examples include the liquid crystal (LC) film technology [**25**], which has been successfully deployed in previous experiments at the BELLA PW [**26**], cryogenic hydrogen jets [**27**], liquid jets [**28,29**] and supersonic gas jets [**30**]. Within the BELLA Center, previous experience with kHz reference lasers [**31**] can be leveraged to support target alignment to the few micrometer scale focal volume via kHz active feedback between 1 Hz PW shots. We will also field HRR detectors to record angularly resolved ion energy spectra. Scintillator based alternatives to the commonly used RCF stacks have emerged to reconstruct the angular proton emission at appreciable energy resolution [**32,33**].

Heavy ion acceleration: We propose to explore laser-driven heavy ion acceleration in the TNSA regime to benefit from their increased energy deposition in a fast ignition target. TNSA results in the acceleration of ions from the target surface layer depending on their charge to mass ratio *q/m* (right side of Fig. 2). Protons, with the highest *q/m* are accelerated most efficiently and reach the highest kinetic energy per nucleon. Carbon and oxygen, which are typically present in the hydrocarbon contamination layer, are accelerated to lower cutoff energies (cutoff energy per nucleon) but can make up a significant portion of the accelerated ion bunch, effectively depending on their contribution to the composition of the accelerated target surface layer [**34**]. Target bulk ions, i.e. metal ions in the case of metal foils, can also be accelerated in case the TNSA field reaches deep enough in to the target bulk, or, if the surface layer is removed for example through inductive heating of the target or laser ablation [**35,36**].

Ion transport and WDM studies: We propose an experiment at BELLA iP2 with an adapted transport beamline to conduct isochoric heating experiments with the optimized TNSA beam and access WDM plasma states. Uniform irradiation of a volumetric WDM sample requires shaping the ion bunch energy deposition profile into a 3-dimensional spread-out Bragg peak. This can be achieved by transporting a broadband portion of the spectrum from the TNSA source to the sample. Permanent magnets and active plasma lenses [**37**] have been successfully used to transport up to 8 MeV LD protons to a sample site for cell irradiations at the BELLA PW [**38**]. We also designed a compact and versatile proton transport and focusing beamline of higher energy ions up to 30 MeV, generated at BELLA iP2, using permanent magnets [**39**]. The beamline can be adapted for different energy ranges and requested energy deposition profiles.

Due to the high energy density and short temporal duration of the TNSA proton or ion beam, heating can occur uniformly and on a picosecond time scale before matter expands hydrodynamically. This allows for heating of plasma to a single-density and single-temperature state. In this environment, fundamental material properties, like the equation of state and opacity that are required to benchmark theoretical plasma models and simulation codes, can be measured [**40**]. Previous experiments have shown successful isochoric heating up to 20 eV with focused TNSA proton beams [**41**].

Ion stopping in WDM: We propose to conduct experiments at the BELLA PW to investigate proton and ion transport and stopping in a WDM sample that has been heated to tens of eV temperatures. While these properties are well known for solids, measurements in the WDM regime are necessary to benchmark theoretical models and simulations that describe charged particle transport in ignition experiments. As TNSA produces a high particle flux with broad kinetic energy spectra and multiple ion species, isochoric heating and simultaneous diagnostic of ion stopping in the created WDM state are perceivable. The picosecond duration of TNSA proton bunches is short enough to probe plasmas and extreme states of matter with high temporal resolution [**42**].

Conclusion

We have presented the outline of an experimental program at the 1 Hz BELLA PW laser that is formulated to research the viability of fast ignition fusion, based on laser-generated protons or ions, as a path to IFE. Specifically, we propose to explore TNSA of protons and heavier ions at increased laser to ion energy conversion efficiency, and the creation and investigation of WDM states with these TNSA ions. These results, in combination with advanced simulation tools, will be used to determine plausible IFE-relevant target design parameters. The result of this program will be a clear picture of the major target physics issues that will need to be addressed with respect to ion fast ignition in the context of IFE.

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