White Paper for *Frontiers of Plasma Science Panel*

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• Statistical mechanics of plasmas	

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	"X"
Oral	X
Poster	
Either Oral or Poster	
Will not attend	

Title:	Laser-matter interaction and ion acceleration with PW laser pulses
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- ***Research frontier* and importance of the scientific challenge.**

The rapid development of laser technology makes it possible to generate very intense and ultra-short bursts of electromagnetic radiation, which inspires the fast growing area of high field science aimed at the exploration of novel physical processes. In particular, the laser acceleration of charged particles is considered one of the main applications of many powerful laser facilities. Such facilities are being projected, built, or already in operation around the world, indicating a high level of interest in studying novel physical processes occurring in electromagnetic radiation interaction with matter. The ultra-short electromagnetic pulses provided by these facilities are able to generate very strong accelerating fields in plasma, which exceed those of conventional accelerators by several orders of magnitude. This potentially results in very compact accelerators providing ion beams with energies ranging from several MeV to multi GeV for many applications.

Ion bunches with energies of tens of MeV have been generated in such micro-meter scale plasma based accelerators. Collimated proton bunches with a continuous, Maxwellian-shape spectrum and energies up to 60 MeV from laser irradiated foils were demonstrated in pioneering experiments more than a decade ago [1]. These triggered an extensive world-wide effort. However, the maximum proton energy reported did not exceed 67 MeV [2].

Only recently, the field has experienced major advances due to the availability lasers with powers of a few-hundred TW and laser pulse cleaning techniques that allow a temporal intensity contrast of 14 orders of magnitude [3]. New and very efficient acceleration regimes with target foils of nm thickness have been demonstrated with energies up to 100 MeV [4, 5]. Monoenergetic proton beams were observed with solid-state lasers and nanofoils [6, 7] as well as with CO_2 lasers and gas jet targets [10].

When an intense laser pulse interacts with a solid target of a certain areal density a steady state can be established such that the restoring force due to charge separation of electrons and ions is equalized by the laser radiation pressure [8]. This balance causes a compression of the electron population (which remains opaque for the laser) and subsequently enables the acceleration of ion bunches with almost solid densities, exceeding the ion density achievable from classical sources by many orders of magnitude. The laser energy is then transferred to the accelerated plasma by the relativistic Doppler effect, commonly referred to as Radiation Pressure Acceleration (RPA) [9, 10]. The prospect of such miniature accelerators has stimulated the rapid development of this very active field of research that is reflected in a large number of publications in highly ranked journals (such as PRL) during the last few years. However, the first experimental indications of such a regime [6, 11] are lacking a full characterization since a stabilization over a broad range of parameters was not realized yet. In addition, the onset of transverse instabilities occurring during the interaction constrains the overall efficiency of the acceleration, i.e. the dense ion layers break apart and their monochromaticity cannot be preserved until the end of the acceleration process [12].

- ***Approach to advancing the frontier and new research tools or capabilities that are required.***

Using a short focal length beam line at state-of-the-art or future (multi-) PW laser facilities, can offer high peak intensities (~10^{22} W cm^{-2}) with multi-ten fs pulse duration. Such lasers can be equipped with pulse cleaning techniques that enable a temporal intensity contrast of >14 order of magnitude at picoseconds before the main laser pulse. Theoretical and multidimensional computer simulations have shown that ion beams of several hundred MeV/u can be expected from the interaction of such laser pulses with different targets (Fig. 1).

There are several mechanisms of laser ion acceleration that are considered relevant to the development of such a laser-driven ion source: RPA [6-8, 10, 13], Magnetic Vortex Acceleration (MVA) [14], and Directed Coulomb Explosion (DCE) [15, 16]. Particle-in-Cell (PIC) simulations of the PW laser interactions with different targets in the RPA, MVA, and DCE regimes show that 200-300 MeV proton beams can be generated. Ultra-thin foil targets, relevant for RPA and DCE regimes, are also very susceptible to transverse instabilities [12, 17] and transverse expansion [18] . Both effects result in an early termination of the acceleration. The application of multi-layer targets is promising to suppress the instabilities [7, 19] and compensate for transverse target expansion [18]. An impressive computational effort has been mounted to both model the proposed acceleration schemes and to guide and interpret the experimental effort. However, the importance of the transverse plasma instabilities, occurring during the interaction, and limiting the effectiveness of acceleration, is not fully taken into account theoretically and computationally. The modification of the target by the laser pre-pulse and its influence on the ion acceleration, the optimization of different acceleration schemes and accounting for ionization and radiation reaction effects at ultra-high laser intensities are the areas of active theoretical and computational studies which need experimental validation.

The different scenarios discussed above put specific requirements on target engineering. Generally, targets range from nanoscopic solid foil targets to macroscopic low density foams or gases. The composition of the target is important and driven by the demand of accelerating a certain ion species or to suppress laser plasma instabilities.

Many applications of using accelerated ions require high energy monoenergetic beams at high energy. For example, to make laser-driven ion acceleration system suitable for biomedical applications, especially for radiation therapy related studies [20], the beam should be accelerated up to 250 MeV for protons or ~400 MeV/nucleon for carbon ions. Energy spread of 1% or a highly controllable spectrum, with dose on the order of $1\text{-}5\times10^{10}$ particles/second have to be demonstrated. We see exciting opportunities to gain a deeper understanding of the fundamental laser-matter interactions at ultra-high intensities and to advance our ability to control ion pulses generated from laser-driven accelerators.

In particular, bulky magnetic lenses and RF cavities for beam shaping and transportation may reduce the compactness advantage of laser-driven ion sources. An attractive alternative approach is to use discharge capillaries [21] as active plasma lenses [22] in combination with superconducting magnets.. Here the particle beam propagates collinear with an externally-driven current pulse inside a plasma, yielding a radial force. With tunable field gradients of a few thousand T/m maintained over several cm in length, active plasma lenses provide the same radial symmetric focusing as at least 3 quadrupoles (triplet).

- ***Impact of this research on plasma science and related disciplines and potential for societal benefit.***

The first area of scientific impact is the advancements in our basic understanding of laser-matter interaction at ultra-high irradiances $>10^{21}$ W/cm^2 that become accessible with advancements in laser technology, targetry and plasma based laser optics (see white paper by W. Leemans et al.). One fundamental question is how well we can steer and direct the flow of energy at ultra-high intensities. The acceleration of ions in the radiation pressure regime is an example of process of fundamental interest, as it is a signature of the basic laser-matter interactions and it promises to lead to the development of intense, high energy ion pulses that can themselves drive matter into warm dense matter states. This is a very exciting prospect, as MeV/u heavy ions would uniformly heat matter over a few tens of microns to temperatures of a few to tens of eV and Mbars of pressures (see white papers of T. Schenkel et al. and J. J. Barnard et al.) . Here, the ion pulse can be synchronized to X-ray or charged particle sources that are also derived from the primary laser pulse for precision studies of e.g. warm dense matter (see white paper of C. G. Geddes et al.). Further, laser plasma ion acceleration has numerous potential applications such as injectors for conventional accelerators, radiation therapy, studies of radiation damage and single event effect in electronics, as well as fast ignition inertial confinement fusion or material sciences [23, 24]. Their unprecedented characteristics, such as short pulse duration, high peak currents and very low transverse emittance, make this technology very attractive.

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Figures (maximum 1 page)

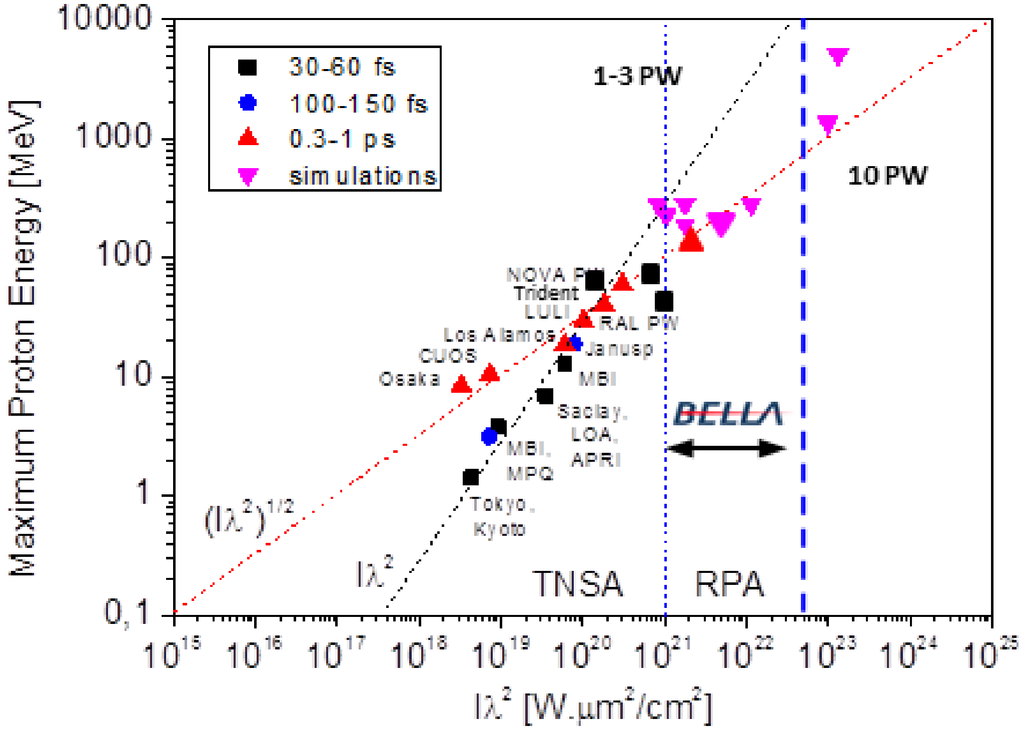

Fig. 1: Scaling of state-of-the-art laser-driven ion accelerators. The vertical dashed blue lines indicate the intensity regime accessible with our proposed BELLA-i user facility at Berkeley Lab (see also the white paper by W. Leemans et al.).