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The integrated laser-driven ion accelerator system and the laser-driven ion beam radiotherapy challenge

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ABSTRACT

Intensity regimes for laser-plasma-acceleration of protons are compared and typical features of the accelerated proton bunch are described. The laser, target and the abruptly induced plasma environment represent the ion source component of the Integrated Laser-driven Ion Accelerator System (ILDIAS). ILDIAS components are defined and some of their key challenges are described. Some requirements of Laser-driven Ion Beam Radiotherapy (L-IBRT) are discussed in terms of proton beam characteristics, beam delivery control and ILDIAS machine performance.

1. Introduction

For the past few decades advancement of particle accelerators has included innovative applications of lasers. The birth of the laser in 1960 followed development of high power microwave klystron tubes by about two decades. Although early high power microwave source development and electron accelerator development benefitted from close association, the ubiquitous laser has nonetheless been the basis for important contributions to particle accelerators as indicated in the following four examples.

Ultrashort pulses from a Ti:sapphire laser oscillator have been used in an electro-optic technique to noninvasively measure picoseocond timing jitter of ultrashort relativistic (29 GeV) electron bunches at the SLAC National Accelerator Laboratory [1]. Also at SLAC 'Q'-switched laser pulses were used to create a gaseous plasma lens in a test beam line (Final Focus Test Beam) to tightly focus 29 GeV positron and electron bunches of short duration [2].

Following pioneering development in 1985 at the Los Alamos National Laboratory, electron RF photoinjectors have proven to be robust sources of high brightness electron bunches notably used for free-electron lasers (FELs) because of the high quality electron beams required [3,4]. Photoelectrons in short (picosecond) bunches are generated as a result of low energy picosecond laser pulse irradiation of metal or semi-conductor photocathodes.

The effectiveness of particle acceleration by an oscillating electromagnetic field scales linearly with its wavelength which can favour direct acceleration by microwave fields over laser fields for a given field amplitude. However, adequate ir laser fields have been reached for direct electron acceleration in a compact dielectric microstructure [5]. Such dielectric laser acceleration, DLA (so-called accelerator-on-a-chip) has already reached acceleration gradients that are an order of magnitude beyond the capability of conventional microwave acceleration. By combining a repetition-rated mode-locked laser system with low (sub-millijoule) pulse energy and a fused silica microstructure, injected 60 MeV electrons experienced acceleration gradients up to 250 MeV/m.

Acceleration of electrons and ions (mostly protons) to high kinetic energies can be driven in plasma fields created by intense laser irradiation of targets. This has been under investigation for more than two decades. Exploration of laser-driven ion acceleration is a natural progression in the evolution of particle accelerator sources. Analogous to the electron RF photoinjector, the laser-irradiated target configuration is a common source in laser-plasma ion acceleration that can be described as a laser-plasma photoinjector for ions where the RF extraction field is replaced by a laser-plasma-acceleration field that is attributed to initial laser-driven charge separation.

Much enquiry at high power laser facilities is aimed at efficiently reaching highest possible ion (mostly proton) kinetic energies driven by highest achievable laser intensities on target. This constitutes exploration of the source parameter space (where the source=laser+target with plasma) aimed at identifying and selecting the most viable sources for laser-driven ion acceleration to energies that are ultimately determined by application requirements. It is also the setting for relativistic laser-plasma engineering as a key part of source development [6]. Given the laser peak power requirements this research is still typically done in a single shot mode (or at very low repetition-rates) which explores intense single pulse (shot) capability. However, for many

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applications, laser-plasma ion acceleration will require stable, controllable, reproducible repetition-rated beams. This can require stable repetition-rated lasers with very high single pulse (peak) power (at PW levels).

I refer to the overall 'machine' as the *i*ntegrated *l*aser-*d*riven *i*on *a*ccelerator *s*ystem or ILDIAS which emphasizes the integrated systems feature. Although the laser-plasma interaction at the target represents the ion source or gun (which we have also called an ion injector for comparison with the electron RF photoinjector), this abrupt interaction can accelerate ions to significantly high kinetic energies (published results at the tens of MeV level for protons). It is an all-optical integrated system for applications only if acceleration at the source yields adequately high ion energy. Consequently, we must also allow for hybrid acceleration as the general case which could include a downstream post-acceleration section (booster). The booster could typically be a conventional (RF) accelerator section. We refer to the hybrid case as the *h*ybrid *i*ntegrated *l*aser-*d*riven *i*on *a*ccelerator *s*ystem or HILDIAS.

It is important to highlight (and even exploit) unique features of laser-driven ion acceleration in attempts to establish utility and application niches. Laser-plasma-accelerated proton bunches are intrinsically of short duration (at the source). Allowing for subsequent propagation debunching to nanosecond durations, fast irradiation and probe dynamics are enabled in the laser case (bunches can be shortened with bunching techniques). Laser-plasma ion acceleration at the target interaction site occurs within a compact space (not including the entire laser system itself) due to the high plasma acceleration gradient. There is a notable potential for generation of multiple synchronous beams (simultaneous acceleration of p and C^{+6} for example [7]) for novel applications and diagnostics. Confirmed ultralow intrinsic bunch emittance at the source indicates its high quality (i.e. high source laminarity).

Three main laser-plasma acceleration regimes are addressed in this report. Typical features of observed energetic proton bunches are described in Section 2. Section 3 briefly presents the ILDIAS concept and progress with some of its components. Requirements for the laser-driven ion beam radiotherapy application (L-IBRT) are discussed in Section 4. Final concluding remarks in Section 5 include suggested strategies to sustain ongoing development.

2. Laser-plasma-acceleration regimes and typical proton bunch features

Laser-acceleration mediated by a laser-driven plasma has been widely studied following reported acceleration to about 58 MeV in 2000 [8]. Three established laser-plasma acceleration mechanisms are Target Normal Sheath Acceleration (TNSA) [9], Breakout Afterburner Acceleration (BOA) [10], and Radiation Pressure Acceleration (RPA) (where the Light Sail version is considered here) [11,12]. Each mechanism will be coarsely described below as a two-stage process. They share the critical requirement for very clean laser pulses which means having a very high intensity contrast to avoid unwanted preplasma formation and target deformation prior to arrival of the main laser pulse. In all cases target (foil) thicknesses (of order λ or much less) are typically much less than laser pulse lengths, $c\tau$ so laser-plasma acceleration occurs within a very small (micro) volume. The progression from the TNSA regime to BOA and ultimately to the RPA regime corresponds to increasing peak laser intensity (therefore mandating higher contrast) and decreasing target thickness. Some distinctive features of these mechanisms are summarized below. A more detailed treatment can be found in a recent comprehensive review [13].

For the TNSA mechanism the collisionless skin depth at the laser wavelength is small enough that target penetration by the laser remains evanescent during the entire pulse [11]. Various absorption/heating mechanisms contribute to 'hot' electron generation at the front (upstream) target surface. High mobility and the extended mean free path of hot electrons allow them to traverse the thin target and escape at the rear surface into vacuum to form a plasma sheath. The sheath establishes a potential distribution that sustains extraction fields at the TV/m level for acceleration of ions (notably protons from rear surface contaminants). The extraction field magnitude depends critically on the hot electron temperature and density. TNSA is therefore based on two key stages: (i) charge separation initiated by laser-driven electron heating at the target front surface followed by (ii) ion acceleration by a plasma field at the rear target surface. Measured proton spectra reveal a quasi-exponential profile with a broad energy spread terminating at some maximum (cutoff) value,ϵ_{cutoff}. Because all ions at the surface 'see' the same extraction field at any given time, protons have the highest emergent velocity (for example, $\frac{v_{Cion}}{v_p} \sim \frac{1}{2}$ according to charge-to-mass ratios). The intensity threshold for relativistic transparency can mark an upper limit for the TNSA regime (e.g. $\sim 10^{20}$ W/cm^2 for tens of nm target thicknesses).

Most of the experimentally observed characteristics of laser-plasma proton acceleration are determined from exploration in the TNSA regime which is more experimentally accessible. Table 1 lists some of these features from which it can be noted that proton emission resembles a pulsed divergent 'spray' for which the spatial velocity distribution is laminar. Furthermore, the emission angle is correlated to particle energy.

At peak laser intensities much higher than those required for TNSA, radiation pressure acceleration (RPA) becomes relevant (10^{22}–10^{23} W/cm^2) [11,12]. Relativistic transparency (for which $\frac{n_e}{n_{cr}} > \gamma$; where n_e is the plasma electron density, n_{cr} is the critical electron density and γ is the relativistic mass factor) is achieved early in the laser pulse making the high laser field interaction volumetric. It propagates through the entire ultrathin target (thickness ~ few nm) ponderomotively accelerating electrons and sustaining a high charge separation field. As with TNSA, RPA can also be described as a two-stage process: (i) a ponderomotively-driven charge separation field that rapidly accelerates ions to co-propagate with electrons forming a moving plasma mirror ('rectification' stage) and (ii) subsequent 'light-sail' acceleration of the electron-ion unit by radiation pressure associated with efficient reflection of Doppler down-shifted laser light ('light-sail' stage as illustrated in Fig. 1). Consequently ion and electron acceleration is a more coherent process with RPA (for which heating can be minimized in a phase-stable mode using circular polarization) where the whole target foil is accelerated as evidenced by the reflected laser waveform that features a time-dependent double Doppler down-shift. Momentum transfer to ions in step (i) occurs

Table 1
Typical 'At-Source' proton bunch features in the TNSA regime.

Charge/duration (peak current)	10's to 100's nCoulombs/~ psec (10's to 100's kiloamp)
Divergence	10's of degrees (full angle)
Extraction (accelerating) Field	~1–10 TV/m
Maximum kinetic energy, ε^p_{max} (protons)	~100 MeV
Energy Spread, $\frac{\Delta\epsilon}{\epsilon_o}$	$>$ 100% (using $\varepsilon_o =$ spectral median)
Transverse emittance, ϵ_x (geometrical – full bunch)	$\sim 10^{-3}$ mm mrad
Repetition-rate	up to 1 Hz demonstrated (equals laser repetition rate)
Efficiency (full ion spectrum), η	0.1 to few % levels $\left(\frac{\text{particle kinetic energy}}{\text{incident laser pulse energy}}\right)$