

Invited Review Article: “Hands-on” laser-driven ion acceleration: A primer for laser-driven source development and potential applications

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Invited Review Article: “Hands-on” laser-driven ion acceleration: A primer for laser-driven source development and potential applications

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An overview of progress and typical yields from intense laser-plasma acceleration of ions is presented. The evolution of laser-driven ion acceleration at relativistic intensities ushers prospects for improved functionality and diverse applications which can represent a varied assortment of ion beam requirements. This mandates the development of the integrated laser-driven ion accelerator system, the multiple components of which are described. Relevant high field laser-plasma science and design of controlled optimum pulsed laser irradiation on target are dominant single shot (pulse) considerations with aspects that are appropriate to the emerging petawatt era. The pulse energy scaling of maximum ion energies and typical differential spectra obtained over the past two decades provide guidance for continued advancement of laser-driven energetic ion sources and their meaningful applications. © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). [<http://dx.doi.org/10.1063/1.4959198>]

INTRODUCTION

The acceleration of ions by means of laser pulses dates back to when lasers became intense enough to ionize matter and create a plasma, a state in which electrons are free and no longer bound to the atomic nuclei. Fundamentally, absorption of laser pulse energy by a target is an electron acceleration process. In a nutshell, plasma electrons that absorb part of the laser pulse energy can subsequently transfer their (laser-inherited) energy to kinetic energy of the ions. The process is best described as plasma expansion. In fact, over time, it became possible to concentrate considerable laser energy to even shorter pulse durations, from μs in the 1960s to a few tens of fs in the 1990s.¹ As of today, the highest available peak (single pulse) power is of the order of 1 PW, that is, 10^{15} W. The key enabling technology providing such high peak power in the laboratory is chirped pulse amplification (CPA),² typically operating at wavelengths near $1\ \mu\text{m}$ (Glass-laser systems) or 800 nm (Ti:Sa-laser systems). At the petawatt (PW) power level, a laser pulse can deliver 20-1000 J within 20-1000 fs where the volumetric energy density can approach 300 gigajoules/cm³ under tightly focused conditions. In general, during the past two decades, transfer of laser pulse energy (i.e., photon energy) to ion kinetic energy (i.e., ion acceleration) has become more directed, more efficient, and more controlled. This novel ion acceleration in extreme fields begins with the interaction of the tightly focused high power laser pulse with the plasma it has generated at a target site (i.e., a highly localized intense laser-plasma interaction). Our goal in what follows is to summarize the basic concepts and ideas for the wider scientific community that might be interested in developing laser ion acceleration, for example, for a specific application.

TAILORING AND DIAGNOSING FOCUSED HIGH-POWER LASER PULSES FOR ION ACCELERATION

Laser ion acceleration requires focusing high power (100s TW to ~PW) laser pulses to high intensity onto special targets. We initially address here some intense laser pulse issues that are critical to these developments. The conceptual high power laser laboratory layout for experimentally investigating and applying laser-ion acceleration as shown in Fig. 1(a) has remained nearly unaltered over the last several decades. Laser pulses are generated, amplified, and manipulated to fulfill the parameter requirements. For a given pulse duration and focal spot size, peak laser power and intensity scale linearly with the pulse energy. Major requirements of the laser pulse also include good focusability to small spot sizes with smooth transverse profile and a well-controlled temporal profile that features excellent contrast. Laser quality is further established by sufficiently large aperture mirrors in the evacuated tubes that “transport” the laser pulse to the experimental vacuum chamber as indicated in Fig. 1(a).

The port through which the laser pulses enter the experimental vacuum chamber represents an important interface. For the successful operation of laser-ion acceleration, the laser-plasma physicist who takes over must nowadays still have broad expertise in both sides of this interface. Laser ion acceleration occurs in an extreme field, a relativistic laser-plasma environment at the target location. Tight focusing to a near-diffraction-limited focal spot size is typically realized with low F/# off-axis parabolic (OAP) mirror. For example, 1 PW focused to a spot of $3\ \mu\text{m}$ diameter yields a peak laser intensity of the order of 10^{22} W/cm² for which the electric field amplitude is about 300 MV/(laser wavelength). The simplest target

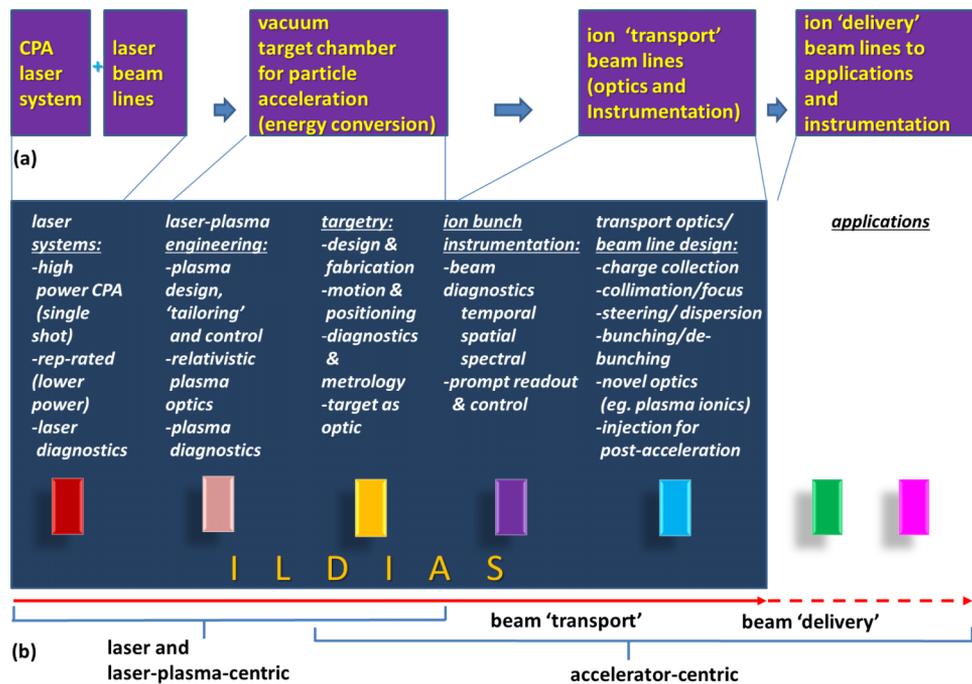


FIG. 1. (a) General hardware sections of the typical laboratory layout for developing and applying laser ion acceleration; (b) the integrated laser-driven ion accelerator system (ILDIAS) concept represents the source machine that is distinct from the application.

is typically a very thin (of thickness 100s of nm up to a few times the laser wavelength) or ultrathin (few to 100 nm thickness) foil that must be positioned and oriented with commensurate precision in (or relative to) the focal plane.

The microscopic processes in play under such extreme plasma conditions facilitate the laser-plasma physicist's main interest. Here, the fundamental processes which are relevant to laser-ion acceleration therefore remain to be described on a qualitative, semi-empirical basis. We refer the more expert reader to Refs. 3 and 4 for a more complete historic treatment. The laser-driven ion acceleration laboratory can therefore be considered in the basic hardware sections sketched in Fig. 1(a). Fig. 1(b) shows the relationship of these laboratory sections to ILDIAS components (which will be further discussed later in this article).

For increasing laser peak power, the intensity contrast becomes an increasingly important pulse parameter. Most target materials start to melt or are ionized at intensities as low as 10^{10} - 10^{12} W/cm². Hence, disintegration of the target must be retarded for the longest possible time, which requires sufficiently high (10-12 orders of magnitude) temporal intensity contrast within picoseconds before the pulse reaches its maximum intensity. But even then, the target has a short and adventurous life. We treat individual particles as components of the "object" target and explain the processes during the short interaction with the laser pulse with the aid of the temporal intensity profile example as shown in Fig. 2. In standard CPA-lasers the intensity gradually rises and eventually exceeds $\sim 10^{13}$ to 10^{15} W/cm², equivalent to an electric field strength of 1-10 V/Å which is the same field order as that which binds electrons to their positively charged atomic nuclei. Hence, within these few picoseconds prior to the peak of the laser pulse, electrons are abruptly removed from their atomic nuclei and the target is transformed into a plasma. As the lightest

particles in the plasma, the now free electrons oscillate in the transverse laser electric field of 0.01-0.1 MV/μm, absorbing and reflecting part of the laser energy. If the intensity would not rise further, the absorbed laser energy would drive a typical plasma expansion which has been studied since the 1960s. The next important stage at 10^{18} W/cm² is of particular interest because the electric field amplitude exceeds a MV/μm; the plasma electrons gain a kinetic energy comparable to their rest energy (0.5 MeV to 0.1 picojoules) and approach the speed of light during phases of the rapid oscillatory motion. Because of this relativistic motion, the Lorentz-force ($\mathbf{v} \times \mathbf{B}$) which pushes the electrons in the direction of laser propagation becomes larger than the transverse force due to the electric field \mathbf{E} . In other words, the radiation pressure of the laser directs the electrons predominantly forward. Ideally, these forward directed electrons accelerate the lagging ions as they pull them along.

However, if the intensity rises too slowly (blue curve in Fig. 2), a large number of electrons are heated in an uncontrolled manner inducing electric fields around the target. Consequently, plasma ions (most often simply protons from the omnipresent hydrocarbon surface contaminants) are emitted as a divergent cone centered about the direction that is perpendicular to the target surfaces and reaching maximum energies up to 70 MeV (with the most powerful lasers). This Target Normal Sheath Acceleration (TNSA) mechanism is to some extent the modern version of plasma expansion that has dominated most laser-plasma experiments over the past two decades. Though already interesting for applications, TNSA prohibits the more desirable radiation pressure acceleration (RPA) mechanism which requires laser pulses with even more abrupt (sharper) temporal profiles in order to avoid premature target expansion (orange curve in Fig. 2). Steepening the leading edge of the laser pulse, temporal profile required some high field

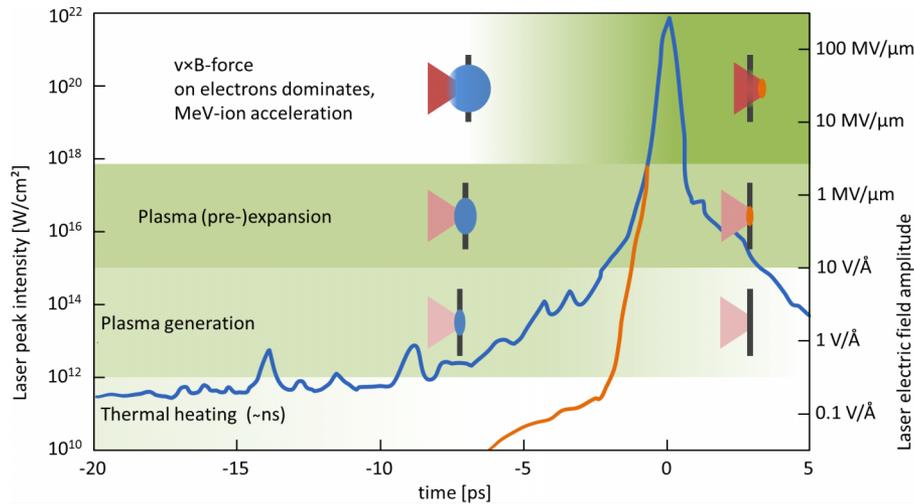


FIG. 2. Logarithmic temporal profile of laser intensity (left axis) and peak electric field (right axis). Typically, the target is ionized and the plasma starts expanding long before the intensity exceeds $10^{18} \text{ W}/\text{cm}^2$ (blue curve and cartoon). For radiation pressure acceleration (RPA), one seeks to minimize the premature expansion by realizing high temporal contrast (orange).

optical engineering using relativistic plasmas (i.e., relativistic plasma photonics). This tremendous technological challenge was initially overcome for small scale 10 TW laser systems in the first proof-of-principle experiments by implementing the plasma mirror that acts as a fast temporal shutter.^{5,6} Irradiating 5 nm thin diamond-like carbon (DLC) foil targets⁷ resulted in $\sim 10^8$ carbon ions traveling at 6%-8% of the speed of light c . Recently, ultrafast temporal steepening could be demonstrated at the 100 TW laser pulse level by utilizing the nonlinearities arising from the relativistic mass increase of the high energy plasma electrons.⁸ In a low density carbon-nanotube plasma directly attached to a 10 nm thin DLC-foil, the laser pulse is focused even stronger (to higher intensity and field) while at the same time the leading edge becomes considerably steeper, delaying pre-expansion of the DLC-foil. This plasma photonic “trick” enabled acceleration of $\sim 10^7$ carbon ions to 15%-20% of c . The examples are particularly promising for the next generation laser systems at the petawatt level which are currently under construction or commence operation at various laboratories around the world (some examples are the Center for Advanced Laser Applications (CALA) in Garching b. Munich, European Extreme Light Infrastructure (ELI) facilities at all three sites, the DRACO/Penelope-laser systems in Dresden, Apollon at Ecole Polytechnique in Paris, VULCAN/ASTRA at the CLF at RAL in the UK, Texas-PW in Austin, Bella at the Lawrence Berkeley Laboratory in Berkeley, PULSER at GIST in South Korea, and J-KAREN-P at the KPSI in Kyoto, see also the laser world-map “International Committee on Ultra-High Intensity Lasers” (ICUIL), www.icuil.org). Relativistic plasma photonics can become a critical pulse-shaping and focusing technology for high intensity (high field) laser pulses.

We coarsely consider anticipated laser and laser diagnostic engineering challenges of the PW era in two categories: (i) addressing the advent of the PW era for laser systems and the ultrafast high-field laser-plasma science they enable in material interactions; and (ii) applications-motivated development of integrated laser-driven ion accelerator systems which will be highly dependent on the developments in

category (i) (more can be found on this in the discussion of ILDIAS). Concerning (i), the advent of the PW lasers and high field laser-plasma science (for which we cautiously assume initial operation at the single shot level or very low repetition-rate) mandates finessed engineering and design of high power adaptive focusing subsystems and other optical controls. This control requires single shot diagnostics of all laser pulse attributes (energy, spectrum, temporal and transverse profiles, time-dependent intensity contrast, etc.) with a repetition-rated readout capability. High power laser systems can benefit from further development of “feedforward” control of laser pulse energy (i.e., where corrections are applied to the actual sampled pulse). The transition from (relativistic) laser-plasma science to (relativistic) laser-plasma engineering refers to the design, development, and control of laser-driven plasmas that are optimally “tailored” specifically for optical function. These specific functions include controlled manipulation of the laser pulse itself, generally referred to as “plasma photonics,” that must necessarily incorporate the relativistic regime. Plasma photonics in general refers to the use of localized plasmas (typically, but not exclusively laser driven) as optical elements that can controllably partition laser pulses (dynamically split into reflected, absorbed, and transmitted portions) as well as manipulate their temporal and spatial profiles (via focusing/defocusing, bunching/debunching, etc., in propagation). This is accomplished on an ultrashort time scale at very high laser fields where the motion (speed) of the mediating electrons is relativistic.

HIGH FIELD LASER-PLASMA PHYSICS AND ION SOURCE CHARACTERIZATION

Most exploratory experiments in laser-particle acceleration concentrate on the characterization of the particles emitted from a target in response to the irradiation by a single, intense laser pulse. Such studies are typically motivated by understanding the microscopic processes mentioned above in more detail and require a diverse methodology.

The features of laser-ion sources (or plasmas optimized for ion emission) can be summarized as follows:

- Co-emission of a mixed ion beam with a variety of elements and charge states, controllable by target composition and treatment.
- Co-emission of a mixed radiation field (bunches of electrons and pulses of electromagnetic radiation ranging from the microwave to hard X-ray and gamma-ray regions).
- Micron source size and divergence half angles from a few to a few tens of degrees.
- Emission times of order of the laser pulse duration, i.e., femtoseconds to picoseconds, with broad energy distributions with (typically) exponentially decaying ion numbers towards the energy end, characterized by the cut-off/maximum energy E_{max} .

As will be discussed later, these specific properties are potentially interesting for applications. On the other hand, they complicate particle (and complementary) diagnosis of the source/plasma. The ideal tool for particle characterization would allow registering all the elements contained in the target, as they will contribute ions in various charge states to the acceleration. The most straight forward solution relies on sampling a tiny fraction of the central part of the otherwise divergent (many degrees half angle) particle plume and analyzing it by electric/magnetic spectrometry (for example, Thomson parabola spectrometers in which ions are separated according to their charge-to-mass ratio and kinetic energy in the detection plane) or time-of-flight spectrometry. If the acceleration is dominated by a single species, in the simplest case protons, the particle depth-dose distributions can be registered in suitable, three-dimensional resolving detectors (or detector stacks) allowing for angular and depth (i.e., energy) resolution. Employing stopping-power calculations, such signals allow for reconstructing the full angular-energy distribution of the source from a single laser pulse. However, the variety of the available detectors and detection methods⁹ can bring inevitable ambiguities of the style (and the accuracy) with which

are reported experimental results, in particular the number of accelerated ions (and therefore important values such as the energy conversion efficiency).

The most commonly measured quantity used to characterize the performance of laser-ion acceleration and to compare experiments amongst each other is the maximum energy E_{max} of the otherwise broad energy distribution with which the ions are emitted. Although E_{max} indicates an important spectral feature, it is not suitable for most applications which require ion bunches with a certain minimal and stable particle number at a specified energy. Nevertheless, experimental campaigns aim to increase E_{max} by manipulating laser and target parameters. As described in the section titled Tailoring and diagnosing focused high-power laser pulses for ion acceleration, the conditions during the interaction of the laser pulse with the plasma are inevitably linked to the laser pulse parameters. Therefore, analytical models can typically predict maximum ion energy to within a factor of 2 or so. Within this accuracy, regardless of the actual acceleration mechanism at play, experimental experience shows that the available laser energy in a high-quality focal spot is the most crucial parameter for maximizing achievable ion energies (Fig. 3). As a useful yet slightly optimistic rule of thumb for considering the low energy laser systems of Joule pulse energy level, Macchi *et al.* found that “under the right/clean conditions, protons can gain 10 MeV of kinetic energy per 1 J of laser energy that one manages to concentrate in the laser focal spot.”¹⁰ This condition would be found in the upmost part of the grey area in Fig. 3 (and even slightly exceed it).

As indicated by the colored horizontal bars, applications of ions can certainly be categorized by the energy range achievable by laser acceleration. It is, however, insufficient to predict requirements and applicability of laser-ion acceleration in a wider scientific sense. Whenever sincere applications are considered, absolute particle numbers and fluence levels (number of particles per unit area) are required for design studies. This means that absolute (differential) spectral amplitudes matter. For this purpose, experimentally measured ion energy distributions are often scaled to higher particle energies

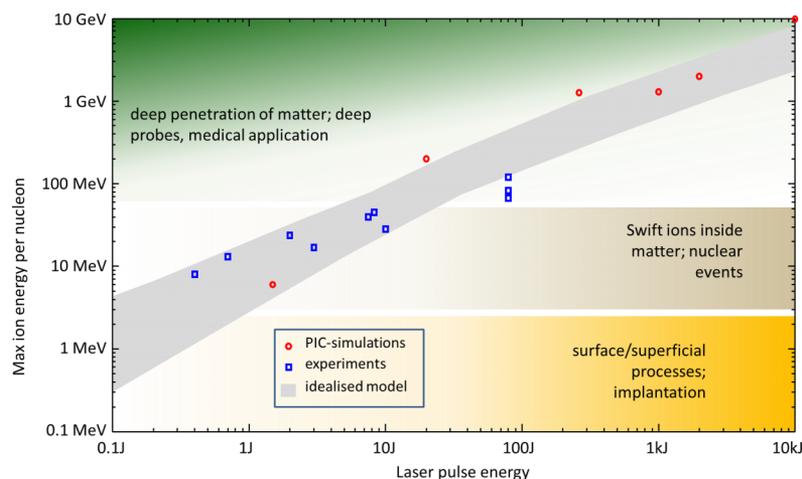


FIG. 3. Maximum ion energy per nucleon E_{max} as a function of laser energy “available on target” (adapted from Ref. 11), blue squares are selected experimental results, red circles represent Particle-In-Cell (PIC)–simulation results. The colored areas address the “type of application” relevant to the available energy range.

(which can be expected from upgraded laser systems), or one relies on theoretical predictions, obtained, for example, from particle-in-cell simulations. In order to reduce uncertainties in such predictions, scaling laws that incorporate not only the maximum particle energy but also more generally the differential spectral amplitudes of particle yields are urgently needed. This similarly requires standardized presentation of experimental results, in particular so-called ion spectra, in the compatible form of absolute differential spectra.

To provide a more general, intuitive guidance for applicants, we expand on the simplest straightforward approach which is to characterize a small sampled portion of the broad energy, divergent plasma bunch (ion plume) emitted into some general direction. As nearly all current experiments are operated in single-shot mode (and even the few systems operating at up to 10 Hz are basically repetition-rated single shot runs), we consider the number of ions ΔN_{ion} per energy “slice” ΔE_{kin} and solid angle increment $\Delta\Omega$ contained in a single bunch as useful quantities for considering potential applications. This allows us to combine several plots into a single figure displaying comparative energy-dependent differential spectra, B_{ion} , based on the exemplary results of laser ion acceleration obtained during the last 20 years:

$$B_{ion}(E_{kin}) = \frac{1}{\Delta\Omega} \cdot \frac{dN_{ion}}{dE_{kin}}(E_{kin}). \quad (1)$$

The energy E_{kin} in Figures 4 and 5 is the kinetic energy per nucleon for protons and other ions, respectively. In order to normalize the typically broad energy distributions, we specify a 1% energy slice (such that $\Delta E_{kin} = 1\% E_{kin}$) which is analogous to conventional synchrotron or neutron source comparisons. The 1% level energy spread would be imposed by ion beamline limits and is acceptable for most applications. The angular divergence (half angle) is usually large, at least 30 mrad (for which the solid angle increment, $\Delta\Omega \sim 3$ msr). Although we consider a standard $\Delta\Omega$ of 1 msr to be significantly less than the intrinsic (at-source) full angular ion distribution, it is nonetheless larger than the acceptance angles that are typical of particle optics in normal (fixed

magnet or warm technology) magnetic quadrupole doublets. Of course, this choice is somewhat arbitrary and limiting when considering more advanced/higher focusing strength ion collection and collimation optics; for example, pulsed solenoids,¹² superconducting magnets, or plasma lenses.¹³ In general, Figures 4 and 5 should be considered for guidance, representing general trends. The conversion of the raw signal registered on the detector, to absolute particle numbers and determining the angle of the beam divergence of the ion bunch bare potential for sizable uncertainties in current experimental campaigns. Note that at the high kinetic energy end of a respective dataset, the evaluation often relies only on a few ions that reach the detector. Differential spectral amplitudes must therefore be interpreted with care in this maximum kinetic energy region.

When considering the comprehensive dataset presented in Figs. 4 and 5, it is helpful to reflect that high-power CPA-laser sources are typically based on two main laser materials. “Glass”-laser systems can provide much higher laser energy but are limited in bandwidth and therefore allow typically pulse durations of several 100 fs, and their repetition rates are limited to a few pulses per hour (as of today with available infrastructures). The corresponding experimental results from such Glass-laser systems are indicated by the dashed lines. The second active medium, titanium-doped sapphire (Ti:Sa) can amplify pulses over a much broader bandwidth. Therefore, these laser systems can deliver laser pulses with a few tens of fs duration and hence require only about one-tenth of the energy needed to reach the peak power levels comparable to those of a Glass system. Ti:Sa results are indicated by the solid lines in Figs. 4 and 5. Note that, although the spectra are single-shot results, the repetition rate capability of employed Ti:Sa laser systems can extend up to 10 pulses per second, i.e., 100 times higher than that with Glass-lasers.

Comparing the dashed and solid lines discloses the most obvious observation, i.e., at a given proton energy the differential proton spectrum obtained with Glass-lasers exceeds the values obtained with “Ti:Sa” lasers by a factor of about 100 or so. This can be attributed to the energy in the Glass laser pulses,

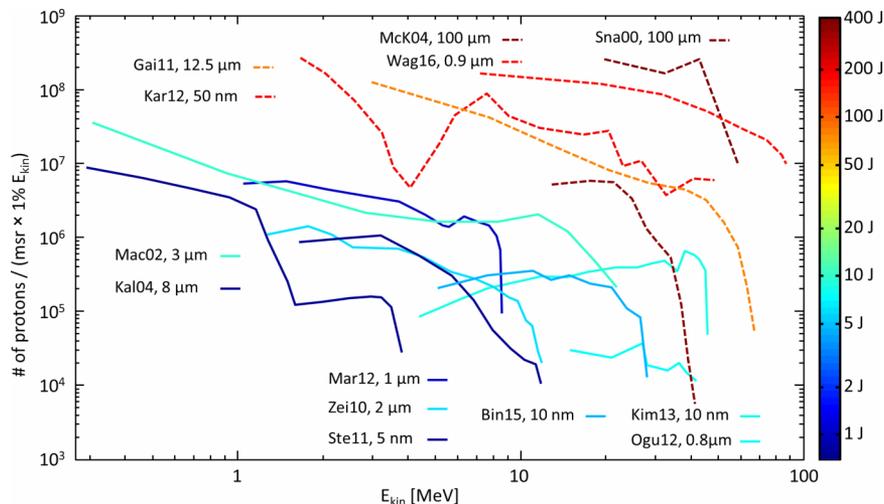


FIG. 4. Reported differential spectra of protons from “Glass”- (dashed) and “Ti:Sa”- laser systems (solid). The color bar represents the laser energy on target with indicated thickness. Publication legend: Sna00,¹⁴ Mac02,¹⁵ Kal04,¹⁶ McK04,¹⁷ Zei10,¹⁸ Ste11,¹⁹ Gai11,²⁰ Kar12,²¹ Mar12,²² Ogu12,²³ Kim13,²⁴ Bin15,⁸ and Wag16.²⁵

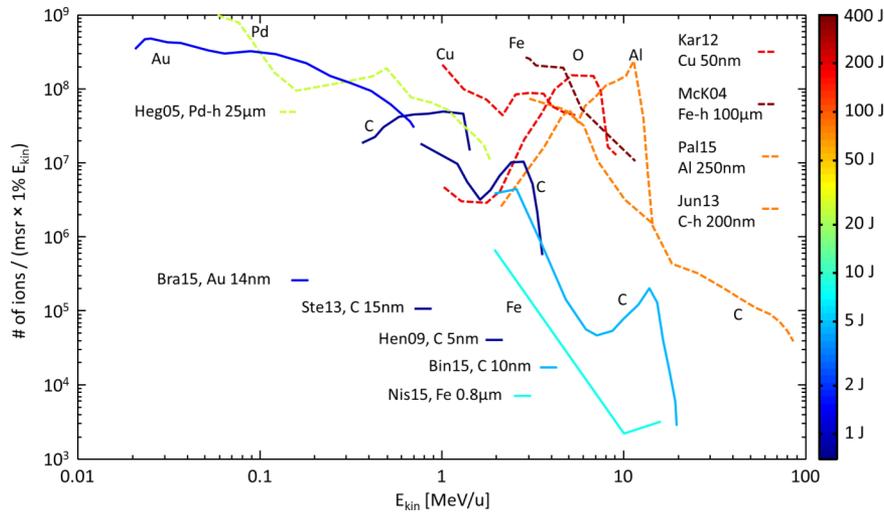


FIG. 5. Reported differential spectra of other ions from “Glass”- (dashed) and “Ti:Sa”- laser systems (solid) plotted in terms of kinetic energy per nucleon. The color bar represents the laser energy on target. The dominant target element and target thickness are indicated, as well as whether the targets were heated (-h). The dominantly accelerated ion species is marked at the corresponding lines. Publication legend: McK04,¹⁷ Heg05,²⁶ Hen09,⁷ Kar12,²¹ Jun13,²⁷ Ste13,²⁸ Bra15,²⁹ Bin15,⁸ Nis15,³⁰ and Pal15.³¹

which is larger by a similar factor, as indicated by the color map along the right margin. Interestingly, this means that for operation at the potentially higher Ti:Sa laser repetition rate, the average ion yield rate (i.e., the number of ions per second) can be similar.

The plotted line-colors (and the corresponding color bar) represent the on-target laser pulse energy. As shown in Fig. 3, the maximum kinetic energy of the protons increases with increasing laser pulse energy. It is noteworthy that for “Glass”-lasers, the spectral amplitudes rapidly drop down at maximum proton energies near 70 MeV. The Ti:Sa results also reveal an interesting trend. In particular, the proton spectrum from Kim *et al.*,²⁴ obtained from the irradiation of 10 nm thin plastic foils, seems to indicate a change of acceleration paradigm that can be attributed to radiation pressure acceleration as indicated by the authors. It should be noted, though, that from the 30 J pulses provided by that particular laser system, 9 J were available on target. This significant lower value of “energy available on target” is the representative for nearly all current experiments performed with Ti:Sa-laser systems. Typically, pulse energy loss is due to the post-compression pulse-cleaning techniques; for example, the enhancement of the temporal contrast by means of a plasma mirror, which is required to enable ion acceleration from very thin targets (compare Fig. 2). The resultant energy reduction by about a factor of 2 is acceptable for smaller laser systems and proof-of-principle experiments. However it becomes even more acute when considering multi-Joule PW-“Ti:Sa” lasers. Regardless of these present losses and other limitations, ultrathin targets do shift proton spectra towards higher kinetic energy, while maintaining comparably high ion yields, i.e., differential spectral amplitudes (compare, for example, Kim13 and Ogu12).

Regardless of the target material, protons (Fig. 4) dominate the ion signal in nearly all the experiments. In addition, carbon and/or oxygen ions are observed, originating from surface oxides, carbides, water or hydrocarbon contaminant layers on the target surfaces. In expansion dominated settings,

the ion species with highest charge to mass ratio dominates the acceleration, i.e., it gains the largest kinetic energy. Contaminant layers can be removed easily by heating the targets prior to the laser shot. Also, oxides or other chemically bonded elements could be removed by sputtering. Fig. 5 presents reported differential spectra for other ions (i.e., heavier than protons) where heated (therefore hydrogen contaminant free) targets are indicated. As explained above, the kinetic energy is given in units MeV per nucleon (i.e., having also factored in the solid angle of the measurement in the spectral yield as indicated in the figures).

As with protons, Glass-laser systems outperform Ti:Sa in terms of heavy ion number. However, it is interesting to note that with sufficiently high temporal contrast, a heavy ion source based on nanometer thickness targets and 1 J Ti:Sa lasers (Fig. 5, Au, Bra15) can exhibit ion yields similar to that from μm -foils irradiated by 20 J Glass-lasers (Fig. 5, Pd, Heg05). The nano-target advantage is clearly suggested in the acceleration of carbon ions to a few MeV/u to 20 MeV/u using “Ti:Sa”-lasers, an energy range that is hardly accessible with μm thickness targets. Although the particle numbers rapidly drop off towards higher energy, the combination of nanometer target thickness with (higher energy) Glass-lasers results in even higher carbon energies (Jun13) as expected from the energy scaling in Fig. 3. As in the proton case, the shape of the carbon ion differential spectra (Ste13, Hen09, and Bin15) with “Ti:Sa”-lasers and of heavier ions obtained with “Glass”-lasers irradiating nanometer foils (O, Kar12 and Al, Pal15) may represent pre-cursors of a transition to new acceleration mechanisms with increasing ion kinetic energy, i.e., laser energy and laser peak power.

DEVELOPING THE INTEGRATED LASER-DRIVEN ACCELERATOR SYSTEM (ILDIAS)

It is clear that procuring high power laser pulses and targetry that can function as suitable ion source components is

a great technical challenge that can significantly contribute to the overall advancement of accelerators (Figs. 4 and 5). The ILDIAS concept directly confronts the laser-driven accelerator challenge.³² Specialized high power laser systems with “tailored” pulses, novel repetition-rated targetry and instrumentation (both for the laser system and the ion transport), specialized plasma generation and plasma photonic processes, and ion optics in transport beam lines together obviate the multidisciplinary collaborative nature of ILDIAS that must be sustained in multiple research communities. ILDIAS is the basic laser-driven ion beam “machine” (i.e., distinct from applications) which is analogous to a synchrotron, for example. It is expected to function at some operating or working energy about which a beamline-limited energy spread is defined. It is noteworthy that this operating energy must be well-below the spectral maximum or cut-off energy associated with the source. Fig. 1(b) illustrates the ILDIAS concept and some useful nomenclature where it is shown that the laser and laser-plasma centric segment is comprised of the laser system, laser-plasma engineering/design, and targetry. The accelerator-centric segment is comprised of targetry (i.e., it is part of both segments), ion bunch instrumentation, and transport optics and beam line design. It is a useful distinction to refer to the localized distribution of photons (laser or otherwise) as pulses and that of massive particles (electrons and ions) as “bunches.” Some brief comments are made below about each ILDIAS component.

As the ILDIAS driver, the need for repetition-rated high power laser pulses that are “tailored” for high intensity and high contrast has already been discussed in some detail. In general, laser pulse controls should also include energy, temporal shape including pulse duration and contrast (as an adjustable parameter), and polarization. Laser systems that produce peak powers up to \sim PW can now be purchased from commercial suppliers. Contrast control, polarization control, and relativistic plasma photonics can act to optimally tailor the pulse (i.e., pulse shaping and focusing on the target). Of course, the size (footprint) of ILDIAS will be determined mostly by the laser size and that of the ion transport beamline. Although there is little requirement for the compact machine prototypes, we anticipate that any compactification would be industrially led under market-driven forces.

The ideal target should be robust (self-supporting), optimized for conversion efficiency and ion yield at desired energies and have repetition-rated capability. As the energy conversion site for ion generation and acceleration, the target may be viewed as the photoanode in a (usually) back-illuminated laser-plasma photo-injector (analogous to the front-illuminated photocathode of the RF photo-injector for electrons). The target or photoanode (typically a thin foil) plus the laser pulse and plasma environment comprise the full ion source (which could also be referred to as the gun). It is also common to refer to photon and particle yields emergent from the target as “secondary” sources where the laser pulse is the primary source. Because the intrinsic “at-source” energy spread can greatly exceed that of the transport beam line, an at-source “slice” efficiency (over a specified limited energy range, δE from E_{low} to E_{high} that matches the ion beamline optics) can be more relevant than

the full spectrum efficiency. Under repetition-rated operating conditions, the source should yield ion bunches at application-relevant energies with an optimized “slice” efficiency (one can also define an energetically broader “source slice” to accommodate tunability of the ion beam line³²). We anticipate that the reduced energy-spread associated with RPA can improve the ion yield in the relevant energy slice (i.e., selectively enhance the differential spectrum amplitude as seen in Figs. 4 and 5). Focusing action at the source has also been demonstrated as a mitigating feature in addressing the large disparity between the large intrinsic “at-source” ion bunch divergence and that accommodated by typical ion beam line optics. For this reason “smart” targetry as the energy conversion site is an important component of both ILDIAS segments as shown in Fig. 1(b). It is also clear that high conversion efficiency and high energy spectra can help to reduce laser pulse requirements. Furthermore, target metrology is needed to confirm the target composition and structure as well as its position and orientation in the vicinity of the laser pulse focal plane. Targetry is a pivotal ILDIAS component for which extended variety and improved performance for repetition-rated operation are essential. For applications, another important issue is the extent to which capacity for increased repetition-rate can compensate for lower single shot yield in some cases.

ILDIAS instrumentation refers to the ion bunch instrumentation for monitoring and for readout used with repetition-rated controls. This can include necessary overlaps with the laser and laser-plasma diagnostics which monitor the ion bunch source. PW era diagnostics for characterizing the single bunch ion yields have been addressed to a limited extent already. A given laser-plasma interaction produces an assortment of energetic particles as well as significant photon yields in the THz-IR-VIS-UV, X-ray, and gamma-ray regions, all produced within a very short time. For the challenging extreme field conditions with high particle and photon fluxes, further developments of particle physics detectors (for example, nuclear-based detection) and new innovations that can exploit this unique “laser-driven”-feature will likely become more relevant for the online monitoring of energetic (tens of MeV) ions and gamma-rays. Ideally this instrumentation should be robust and noninvasive with resolution adequate to reveal single bunch temporal (longitudinal) and spatial (transverse) profiles and a prompt detector readout rate for resolving single bunches (i.e., readout rate exceeding the ILDIAS repetition rate in operation). In addition, the capability for reliable performance in a high peak current environment is important. As with targetry, ILDIAS instrumentation exhibits a wide variety of potential technologies.⁹ Noteworthy is the potential for diagnostic use of synchronous laser probe pulses, ideally frequency-shifted with respect to the drive laser pulse and its harmonics, which is another unique ILDIAS feature. ILDIAS ions (those to be transported within ILDIAS for “delivery” to an application or experiment) outside the spectral region of the source slice can nonetheless be useful in monitoring ILDIAS machine performance and exercising machine controls. This is also true for other photons and particles (e.g., electrons and other ion species) that synchronously emerge from the source as artifacts of the laser-plasma acceleration process.

Consequently, the following three categories of comparison and correlation will be important for the control of reproducible stability in repetition-rated machine operation: pulse-to-pulse, bunch-to-bunch, and pulse-to-bunch.

With ILDIAS there is an opportunity for innovative ion transport optics and beamline design (architecture). Within ILDIAS machine we refer to the ion beam “transport” reserving the term “delivery” distinctly for optics and the beamline to an application (as indicated in Fig. 1(b)). This means that “transport” is machine specific and “delivery” is application specific. Ion bunch transport can feature a mix of conventional and innovative ion optic elements. Of course, size/cost reductions apply to the beamline component of ILDIAS as much as to the laser system. Similar to the relativistic optical engineering opportunities with “plasma photonics,” we can also anticipate novel development of “plasma electronics” and “plasma ionics” as plasma optics components for electron and ion beam manipulation, respectively, in transport. The focusing strength of a localized plasma can exceed that of conventional quadrupole magnets by orders of magnitude.^{33–35} Engineering and design of plasma-based particle optics can become highly relevant to future accelerators where the availability of multiple synchronous laser pulses can facilitate this opportunity. For upstream collection and collimation optics (nearest the ion source), the key challenges are associated with handling the large angular divergence and energy spread intrinsic to the laser ion acceleration process. Concerning this and as mentioned in the brief discussion of targetry, laser ion acceleration in the RPA regime and “at-source” focusing are potential mitigating measures that need further development. On the other hand, the intrinsically large angular divergence and energy spread can inspire creative beam line architecture, especially for correlated bunch diagnostics. Reported demonstrations of innovative active optics include the pulsed high field solenoid¹² and other ion-optical elements constituting a complete transport beamline,³⁶ as well as the laser-induced micro-plasma lens¹³ or target-integrated post-accelerators,³⁷ all of which also spectrally filter the ion bunch spectrum. The micro-plasma lens is a “plasma ionics” element which we distinguish from plasma photonics and plasma electronics elements (the latter two have also been demonstrated). Active ion optics elements will need to operate with repetition-rate ~ 10 Hz or more. Active spectral modulation and ion bunching can also be accommodated in the ILDIAS transport beamline (to offset the natural debunching during propagation that establishes a negatively chirped bunch³⁸). As has been mentioned concerning the laser system, a compact beam line is not critical at the prototype development stage.³⁹ Nonetheless, market-driven forces might motivate some compactification of ion optics by the commercial suppliers.⁴⁰ Finally, it is also clear that ILDIAS can be considered either as a stand-alone all-optical accelerator machine or as an accelerator injector (i.e., a small low energy accelerator that injects ions into a more conventional post-accelerator section) without beam bunching and/or chopping requirements.

The ILDIAS should not be viewed as a replacement for the conventional (i.e., non-laser) accelerator (in this case, we could reasonably expect that it would need to match or advance the performance of some “future” state-of-the-art machines).

Associated with advancement toward greater scientific and technical maturity is a judicious pursuit of niche applications that should ideally exploit the key unique features of laser-acceleration. These key features include capability for delivering short and ultrashort bunch durations, potential for synchronous delivery of multiple ion beams which can include multiple ion species and electrons, and the availability of synchronous laser probe pulses for diagnostics and control. Application requirements can vary significantly with laser-driven ion beam radiotherapy (LIBRT) being one of the most stringent and longer term.

EN-ROUTE TO APPLICATIONS

We have already indicated that ion bunches, abruptly accelerated from micron-sized sources, are emitted (within less than a picosecond) with a characteristically broad angular divergence of intrinsically ultra-short bunch duration at the source. For the TNSA regime, reported ion energies are typically the maximum values of an energy spectrum that exponentially decays with increasing energy. Therefore, the energy spread of this emergent bunch into a cone of high divergence features an energy spread, $\frac{\Delta E}{E_0}$, which can exceed 100%. It would seem that the typical ion yield of laser-driven particle acceleration is fundamentally far removed from that obtained with conventional acceleration technology. The major distinctions of the laser-driven case can bring unique features and new accelerator challenges.

Meaningful applications that can mandate a broad range of delivered ion beam requirements will be the motivation for continued ILDIAS development. Strategies for ongoing ILDIAS research and development must be guided by the notable diversity of needed ion beam parameters. For example, parallel pursuit of the nearer term, more doable applications are clearly beneficial. Furthermore, the ILDIAS research and development is ideally pursued in two parallel paths: (a) delivery of stable reproducible beam parameters at lower ion energies that can therefore reduce laser power requirements and facilitate repetition-rated operation with simple targetry; and (b) exploration of the highest possible ion energies and conversion efficiencies with the highest achievable laser powers and “smart” targetry in single shot (or low repetition-rate) laser-plasma experiments. In path (a), ILDIAS feasibility can be demonstrated as a system (scientifically, technically, and engineering-wise) with a repetition-rate at reduced energy that can be used as an ILDIAS test bed and for applications. In path (b), ion energy can be increased by exploration of the source parameters extreme with the highest power/intensity laser-plasma experiments. It is clear that these paths would progressively merge with the development of higher energy ILDIAS.

Regardless of the final implementations, the already accessible energies up to tens of MeV/u offer the possibility to engage in a wide range of the ILDIAS applications on the path towards the most ambitious goal of LIBRT, which aims to exploit the therapeutic advantages of ion-tissue interaction in matter⁴¹ with more compact footprints for production and steering of energetic ion beams inside the patient in comparison to the current commercially available solutions.⁴²

To this aim, first radiobiological investigations with *in vitro* cell cultures recently demonstrated the feasibility of meeting all prerequisites for biomedical sample irradiation at accessible low proton energies of few MeV/u, including rigorous absolute dosimetry for controlled delivery of clinically relevant fraction-like doses of few Gys in multiple-⁴³ or single-⁴⁴ laser shots. Furthermore, new milestones on the near horizon include small-animal *in vivo* studies and biological experiments addressing the implications of the unique features of laser-driven ion beams, in terms of very elevated local dose rates (towards Gy/ps or more) and, more importantly, the intriguing possibility to produce multiple ion species (e.g., protons and carbon ions) of different biological effectiveness in the same laser-target interaction (or from multiple targets irradiated by a common parent laser pulse). For LIBRT, all these aspects will have to be carefully evaluated in connection with the recent findings suggesting new signaling pathways elicited by the ion interaction in the tissue,⁴⁵ which might be influenced by the peculiar characteristics of the laser-driven particle acceleration.

Beyond applications to therapy, new opportunities are also being explored in the context of ion-based transmission imaging. Here, the specific laser driven bunch characteristics of large divergence and broad energy spread has potential benefits. However, the final ILDIAS realizations and applications of this capability will ultimately depend on the actual beam performance in terms of achievable ion energies, stability, repetition rates, and progress in online detector systems. In this endeavor, major challenges to overcome on the way towards special applications such as LIBRT will include reduction of size (footprint) and costs of PW laser systems and ion beam-lines, while extending the performance to application-relevant repetition-rates (typically 10 Hz or more).

Regarding compactness and cost as major challenges for LIBRT (and potentially other applications), we do not require this for early prototypes that can be strictly aimed at demonstrating adequate application-relevant performance. Concerning the laser, the cost and size of high power systems continue to increase with increased pulse power capability which means that an inflection in this behavior is yet to occur. The tacit assumption of an eventual industrially led cost and size reduction must likely be market-driven and commercially motivated. Particularly for higher energy ILDIAS, the requirement of adequate cost reduction and compactification as a key “enabler” for selective applications also means that, apart from cost/size considerations, the science and technology basis (aspects of which have been addressed in this work) for scaling in engineering and design must be well-established for both the ILDIAS and the application.

CONCLUDING REMARKS

In this PW era, the role of relativistic plasma optics (photonics, electronics, and ionics) presents new engineering opportunities for designing and controlling extreme field laser-plasma interactions that usher innovation to advance particle accelerator technology. This is equally the case for energetic particle sources, particle beam manipulation (such as plasma

focusing), and novel diagnostic photonic techniques. As a novel contribution to accelerator advancement, such finessed developments must evolve intrinsically with high power laser drivers.

Ideal applications will be those that can meaningfully exploit unique features of high power lasers and laser-driven particle acceleration (which have been mentioned). Early quantitative assessment of projected markets for niche applications will also be critical for steering continued development and diverse application of the ILDIAS machine. En-route to the more challenging longer term aspirations (such as LIBRT), it is important to document shorter term accomplishments which can serve as milestones to mark the progressive advancement and maturity of ILDIAS science and technology.

As the enabling machine, ILDIAS is a sophisticated multi-faceted effort that extends relevant science, technology, and engineering well-beyond the limited setting of the laser-plasma experiment. It directly confronts the laser-driven challenge as one of the novel accelerator advancement using the high power laser drivers for which an integrated system mindset is essential.

Figuratively, we must first “learn to walk” with this exciting new technology which, although a natural next step, is still at an embryonic stage in the world of accelerator development.

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