ADVANCEMENTS IN LASER TECHNOLOGY AND APPLICATIONS TO ACCELERATORS*

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Abstract

A brief review on the emergent applications of laser technology to particle accelerators is provided. Important developments of key elements in laser technology that lead to the applications are described.

INTRODUCTION

Advancements in laser technology have dramatically expanded the applications of lasers to particle accelerators. Today, lasers have been used for accelerators in a broad range from operational systems such as nonintrusive particle beam diagnostics instruments, to elaborate applications with high technical readiness levels including, for instance, photoinjectors, a laser assisted foil-less charge exchange injection scheme and Compton scattering-based light sources, and finally to exotic topics such as laser driven electron/ion accelerators. This talk reviews recent experimental results achieved in the above applications, their requirements on laser parameters and challenges that require future laser technology development. Important technical elements such as the femto-second pulse generation, the burst-mode optical amplifiers, the beam combining from laser arrays, and the power enhancement optical cavity will be briefly described.

LASER TECHNOLOGY ADVANCEMENTS

Ultrahigh-Intensity Pulsed Lasers

The remarkable progress in the application of lasers to accelerators was largely attributed to the invention of the chirped pulse amplification (CPA) technique [1]. Prior to CPA, the maximum laser peak power was below 1 GW and the maximum achievable laser intensity stayed around 10^{14} W/cm^2, a limitation due to the nonlinear effects and catastrophic optical damage of the optical components. The core of the CPA technique is that it stretches the pulse duration before the amplifier, maintains the intensity below the amplifier damage threshold, and compresses the pulse in air or vacuum to avoid any possible nonlinear effect. Today, CPA is the only technique for amplifying an ultrashort laser pulse up to the petawatt (10^{15} W) level. The main gain materials used in CPA are solid-state media such as Ti:sapphire or Nd:Glass, which can store about a thousand times more energy than dye or excimer lasers used earlier.

Table 1 lists the parameters of a few ultrahigh-intensity lasers in various facilities. Focusing petawatt pulses onto small spots can produce extreme power densities of 10^{18} to 10^{21} W/cm^2. Such high power densities can accelerate electrons to relativistic speeds, generate MeV protons, and produce x-rays and gamma rays. As we see in the later part, many of the lasers in Table 1 have been used for these purposes.

Table 1: Ultrahigh Intensity Lasers

Facility	Laser Type	Peak Power	Pulse Width	Rep. Rate
UT Austin	Nd:Glass	1.1 PW	167 fs	10 Hz
HERCULES (U Michigan)	Ti:Sapphire	300 TW	30 fs	0.1 Hz
Vulcan (RAL)	Nd:Glass	1 PW	700 fs	
LLNL	Ti:Sapphire + Nd:Glass	1.5 PW	440 fs	10 Hz
Gekko (Osaka)	Nd:Glass	500 TW	500 fs	3-4 Hz
LOA	Nd:Glass	100 TW	25 fs	10 Hz
MPQ	Ti:Sapphire	20 TW	450 fs	10 Hz
PHELIX	Nd:Glass	1 PW	500 fs	
LULI	Nd:Glass	100 TW	300 fs	10 Hz
Ref. [2]	Yb Fiber	1 GW	700 fs	100KHz

Laser Array Beam Combination

In many applications such as the Compton scattering based light source or laser based collider design, (X-ray/γ-ray) the yield and luminosity are important factors. Such applications require not only high peak power, but also high average power of the laser system.

Increasing the cavity volume will raise the laser power but this approach has a physical limitation. An alternative approach to building high power lasers is to use arrays of relatively lower power lasers. As a matter of fact, many large laser facilities obtain extremely high power intensities through beam combining of a large number of high power lasers. In general, beam combining requires that the beams from the array elements be combined to have the propagation characteristics of a single beam. One way of scaling up the laser power is to incoherently combine the laser beams via multiplexing in position, angle, wavelength or polarization. As an example, a 2-MW peak power was obtained by wavelength combing from 4 pulsed photonic crystal fiber lasers [3]. A drawback of the incoherent beam combining is that the brightness of the total beam from the laser array cannot exceed that of each individual beam.

The limitation of the brightness does not apply to mutually coherent beams since they occupy the same elements in phase space and behave as if they came from one coherent source. Therefore only coherent beam combining allows truly scalable output powers and diffraction-limited quality of the combined beams. Primary approaches to get mutually coherent beams are

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external optical phase control by a master oscillator through injection-locking or amplification or self-organizing of the oscillators by coupling through evanescent/leaky waves or common resonators. Coherent beam combining has been applied mainly to semiconductor lasers [4] and fiber lasers [5,6] because of their ease in building in array formats, high efficiency, and the ability to get near-diffraction-limited beams from individual elements. Recently, the Northrop Grumman group demonstrated over a 100 KW average power from a coherently combined solid-state laser array seeded by ytterbium doped fiber amplifiers [7].

Power Enhancement Optical Cavity

In many laser-particle interactions, due to the very low cross section, the photon-particle interaction results in a negligible loss to the laser beam power. Therefore, it is expected that the average power requirement from the laser can be significantly reduced by recycling the laser beam within an optical cavity. Different cavity configurations such as Fabry-Perot, ring cavity, or cavity with built-in harmonic generation crystals have been investigated. Table 2 lists a few recent developments. Optical cavity stabilization technology has been well developed for low-power, infrared, and often continuous laser beams. However, optical cavities proposed for accelerator applications are frequently required to recycle high intensity UV laser beams, operate within a high vacuum, and survive in an environment with high radiation dose. These constraints impose severe technical challenges on the development of the optical cavity to be used in accelerator facilities.

Table 2: Optical Cavity Development

Finesse	Wavelength	Pulse Width	Reference
16000	657 nm	CW	8
349	835 nm	3.4 ps	9
3000	800 nm	52 fs	10
6000	823 nm	63 ps	11
2000	1560 nm	150 fs	12

APPLICATIONS TO ACCELERATORS

Laser-Based Diagnostics

Laser-based nonintrusive beam diagnostics have almost no risk for causing equipment damage and can be conducted at operational particle beam parameters, i.e., high beam current, long pulse duration and/or high repetition rates. A number of laser-based diagnostics systems are operating in accelerator facilities. One example is the system installed in the accelerator test facility (ATF) damping ring at the High Energy Accelerator Research Organization (KEK) to measure a low-emittance electron beam [13]. At the Spallation Neutron Source (SNS), several laser-based beam diagnostics instruments have been developed or are under construction. Recently a large scale laser wire system was brought into operational service for tracking the H^- beam profiles in the superconducting linac (SCL) [14]. This system consists of 9 measurement stations and can be readily extended to measure profiles at each of the 23 cryomodules (or 32 cryomodules in the upgrade project) in the SCL. Laser-based longitudinal bunch measurements in thet MEBT and beam emittance measurement in the HEBT are also under development.

For the above beam diagnostics, the laser power requirement is relatively easily met by commercial available Q-switched or mode-lock laser products. Optical engineering efforts are required for specific applications. At KEK, a Fabry-Perot optical cavity was built to achieve power amplification and small laser beam sizes. At SNS, an active stabilization scheme was designed and installed to maintain a high spatial (pointing) stability of the laser beam to produce an acceptable beam size and position at all profile measurement stations over 250 meters.

Photoinjectors

Photoinjectors are widely used to provide sources of high brightness electron beams for studies in accelerator science, plasma wakefield acceleration, future free electron lasers and linear colliders [15]. Advantages of photoinjectors are their abilities to provide polarized electron beams and generating extremely short, picosecond pulses, each made up of a “bunch” of electrons.

Table 3 lists the main laser parameters used in photoinjectors at a number of facilities. Most photoinjector lasers have a burst mode amplifier structure [16]. A typical photoinjector laser system consists of a seeder that is usually a mode-locked laser providing ps or fs pulses at high frequencies (MHz-GHz), a pulse picker that selects only a portion (macropulse) of the seeder output for amplification, multiple-stage amplifiers to boost the power of the macropulse, and harmonic generation crystals to convert the wavelength from infrared (seeder output) to the UV regime so that electrons can be released in a metal with a sufficient energy to escape into vacuum. Rapid progress has been obtained in the development of the laser technology for photoinjectors in recent years [16].

Laser Stripping

The Spallation Neutron Source (SNS) utilizes charge-exchange injection to “stack” a high-intensity proton beam in the accumulator ring for short-pulse neutron production. In this process, a 1 ms long H^- beam pulse is transported to a carbon stripping foil located at the injection point of the ring. The electrons are stripped and the resulting proton is merged with previously accumulated beam. This injection scheme is central to the operation of many facilities, including the SNS, J-PARC, ISIS and PSR. As the beam power of the SNS is increased from the 1.44 MW design to more than 3 MW as envisioned in the SNS Power Upgrade project, the stripping foils produce uncontrolled beam loss due to excessive heat load, which is one of the main factors limiting beam power in high intensity proton rings.

A “foil-less” charge exchange injection method was first proposed in the 1980s by using a field dissociation process. This scheme requires an impractically large laser power, which is indeed the central difficulty involved in ionizing neutral hydrogen. Recently, Danilov et al. [17] came up with a three-step scheme for laser stripping. The 3-step scheme works as follows: First, H^- ions are converted to H^0 by stripping off the first electron in a magnetic field; then H^0 atoms are excited from the ground state (n = 1) to the upper levels (n ≥ 3) by a laser, and the excited states H^{0*} are converted to H^+ by stripping the second electron in a second magnetic field.

In a proof-of-principle experiment, a third harmonic beam from a Q-switched laser was used for stripping. The laser generates 30 Hz, 6 ns pulses with a peak power of ~10 MW at 355 nm. The stripping efficiency reached 90% [18]. A simple multiplication of 10 MW laser peak power, used in the first experiments, and the duty factor of the SNS beam (6%) yields an average laser power of 0.6 MW at 355 nm to strip the entire ion beam. Obviously, this power is too large to make the device practical. Therefore, a number of approaches have been studied to mitigate the requirement of peak/average laser power. First, a burst-mode laser system has been designed and a prototype model has been fabricated to match the temporal structure of the laser pulses with the ion beam. An alternative approach is to use a Fabry-Perot resonator to recycle the laser beam at the stripping site.

The 3-step laser stripping method can be applied to other facilities where the charge-exchange injection scheme is employed. An example is the Project X [19]. Since in Project X, the H^- is converted to protons at 8 GeV, lasers with longer wavelengths can be used due to the larger relativistic factor. In Table 3, we summarize the laser parameters for the SNS intermediate stage and the final stage laser stripping experiment as well as a design example for the Project X laser stripping.

Table 3: Laser Parameters for Photoinjector and Laser Stripping Experiment

	λ (nm)	Micropulse Length	Micropulse Frequency	Micropulse Energy	Macropulse Length/Rep Rate	Power in Burst	Average Power
Fermilab NICADD Photoinjector	351	5 ps	81.25 MHz	20 uJ	800 us @ 1 Hz	1.6 KW	1.3 W
TTF Photoinjector	262	10 ps	1 MHz	53 uJ	800 us @ 10 Hz	53 W	0.4 W
FLASH Photoinjector	800	7 fs	1 MHz	1 mJ	800 us @ 10 Hz	1 KW	8 W
European XFEL Photoinjector	800	10 fs	4.5 MHz	5 mJ	650 us @ 10 Hz	22 KW	150 W
NLS Photoinjector	800	30 fs	1 MHz	50 mJ	CW		50 KW
CEBAF Photoinjector	780	100 ps	499 MHz	4 nJ	CW		2 W
LCLS Photoinjector	255	10 ps	119 MHz	2.5 mJ	1-40 micropulses @ 120 Hz	300 KW	<12 W
SNS Laser Stripping (Intermediate Stage)	355	50 ps	402.5 MHz	50 uJ	10 us @ 10 Hz	20 KW	2 W
SNS Laser Stripping	355	50 ps	402.5 MHz	50 uJ	1 ms @ 60 Hz	20 KW	1.2 KW
Project X Laser Stripping	1064	81 ps	325 MHz	1.2 mJ	1.25 ms @ 5 Hz	390 KW	2.4 KW

Table 4: Parameters of Laser Compton Scattering

Facility	Laser System	Wavelength	Pulse Width	Pulse Energy	e-beam Energy	X-/γ-ray Energy	Yield
U. Tokyo [20]	Nd:YAG	532 nm	10 ns	25 mJ	45 MeV	10-60 KeV	10^5 Hz
KEK [21]	Nd:YAG	1064 nm	7 ps	112 uJ	50 MeV	30 KeV	10^5 Hz
BNL/ATF [22]	CO_2	10.6 um	6 ps	2 J	64-72 MeV	8 KeV	10^8 per shot
AIST/Japan [23]	Ti:Sapphire	800 nm	100 fs	100 mJ	40 MeV	20-40 KeV	10^6 Hz
RadiaBeam [24]	Nd:YAG	532 nm	10 ps	620 mJ	547 MeV	10.8 MeV	10^{14} Hz
JAEA [25]	Nd:YAG	1064 nm	1 ps	1.8 uJ	350 MeV	0.5-9 MeV	10^{13} Hz
ELSA/France [26]	Nd:YAG	532 nm	30 ps	200 mJ	19 MeV	13.6 KeV	10^8 per pulse

Inverse Compton Scattering

When photons are scattered by charged particles, the energy is transferred from the photons to the electrons and the process is known as the Compton scattering. Inverse Compton scattering (ICS) occurs when the particles are no longer considered to be at rest and in this case the energy is transferred from the electrons to the photons. In particular, when relativistic electrons are subjected to an intense laser beam, the ICS can produce substantial fluxes of photons at a broad spectrum from UV wavelengths to γ-ray region. As high intensity lasers have become more and more available in the recent decade, ICS becomes an important means for high flux generation of X and γ rays with unprecedented characteristics of brilliance, tunability, high monochromaticity and rapidity, with radiation pulses in the picosecond to femtosecond duration range and fluxes of 10^{11} photons/s and higher, within a narrow bandwidth.

Table 4 summarizes recent experimental demonstrations [20-23] and ongoing projects [24,25] on Compton scattering based light sources. High power lasers are required to generate high flux sources. On the other hand a relatively compact laser with a moderate cost is preferred for a practical system. This was made possible by employing an optical cavity to recycle the laser beam since the cross section of Compton scattering is very low and the resulted optical loss is negligible. Indeed in a number of experiments [20,21], optical cavities with finesses of a few tens to several hundreds have been used to increase the X-ray yield by one to two orders of magnitude. Such a design is also included in several ongoing projects [24,25] for the generation of large-flux γ-rays.

Laser Wakefield Plasma Acceleration

The accelerating gradients in conventional RF linacs are currently limited to ~100 MeV/m, partly due to breakdown that occurs on the walls of the structure. Ionized plasmas, however, can sustain electron plasma waves with electric fields easily exceeding 10 GeV/m, which is approximately three orders of magnitude greater than that obtained in conventional linacs. As first proposed by Tajima and Dodson [27], plasma waves can be induced by a sufficiently intense laser pulse. When an ultrashort and ultraintense laser pulse is propagating through an underdense plasma, electron plasma waves are generated by the ponderomotive force of the laser field in the wake of the laser pulse, in a similar way that waves are caused in the wake of a fast moving ship. Remarkable results have been achieved on high quality beam acceleration in the recent decade. A GeV electron beam from a cm-scale plasma was obtained at Lawrence Berkeley National Laboratory [32]. The success greatly encouraged accelerator scientists to conceive of very compact accelerator structures based on laser plasma acceleration for the future colliders.

Table 5: Laser peak power (P), pulse width (τ_w), laser strength parameter (a_0), center energy of the electron beam (E), and electron charge (Q) in recent laser wakefield plasma acceleration experiments.

Facility	P (TW) @ τ_w (fs)	a_0	E (MeV)	Q (pC)
LBNL [28]	9 @ 55	2.2	86	320
RAL [29]	12 @ 40	1.1	78	22
LOA [30]	24 @ 30	1.3	170	500
LOA [31]	24@ 30	1.3	117	19
LBNL [32]	40 @ 38	0.8	1000	30
Heinrich [33]	40 @ 80	4.8	47	0.3
MPQ [34]	18 @ 42	0.8	260	45
MPQ [35]	20 @ 42	0.9	198	10
JAEA [36]	2 @ 70	0.6	14	22
U. Michigan [37]	40 @ 30	2.2	320	~5

Table 5 shows a list of recent experimental results on high-quality electron beam acceleration. All lasers are Ti:Sapphire CPA systems. Most of the experiments produced electron beams with only a few percent energy spread. The laser irradiance ($I\lambda^2$) is characterized by $a_0^2 \cong 7.3\times10^{-19} I(\mathrm{W/cm^2})[\lambda(\mu\mathrm{m}^2)]^2$ where I is laser intensity, λ is wavelength, a_0 is the peak amplitude of the normalized vector potential of the laser field [1] and a_0 ~ 1 corresponds to a relativistic laser intensity.

Laser Driven Ion Acceleration

In recent years, a novel method of laser driven ion acceleration was realized by impinging an ultraintense (10^{18}–10^{21} W/cm^2) laser pulse on a thin foil target. In a number of experiments, protons with energies up to several tens of mega-electron-volts were detected behind thin foils.

Different mechanisms were proposed to account for the phenomenon depending on the thickness of the target. When the target thickness is within the range of a few to several tens of microns, target normal sheath acceleration (TNSA) was found to be the predominant mechanism leading to the emission of multi-MeV, high-quality ion beams [43,45]. In this case, fast electrons ponderomotively accelerated by the laser pulse at the front irradiated surface of the target propagate through the target and exit the rear, setting up a large electrostatic field (of the order of TV/m) due to the charge separation between the escaping electrons and the ions at the rear surface. Another mechanism, radiation pressure acceleration (RPA), was proposed when a thin foil is irradiated by a circularly polarized laser pulse at normal incidence [41,44]. In this case, particles gain energy directly from the radiation pressure (RP) exerted onto the target by the laser beam.

Table 6: Laser peak power (P), pulse width (τ_w), laser strength parameter (a_0), maximum ion beam energy (E_{max}), and conversion efficiency (ε) in recent laser driven ion acceleration experiments.

Facility	P (TW) @ τ_w (fs)	a_0	E_{max} (MeV)	ε
LLNL [38]	1000 @ 500	15.5	58	12%
ASTRA [39]	3 @ 60	1.8	1.2	0.7%
CRIEPI [40]	2 @ 60	2.2	15	0.2%
Saclay Laser [41]	10 @ 65	2.1	5	
RAL PW [42]	570 @ 700	12.7	44	7%
LULI [43]	100 @ 320	0.9	7.3	4%
MPQ [44]	30 @ 45	4.9	71	2.5%
RAL [45]	240 @ 50	18.1	60	
JAEA-KPSI [46]	4 @ 40	6.8	1.9	10%

Many experiments have been conducted on different types of target foils with thicknesses varying from 30 nm to 100 um. Table 6 lists the parameters of the laser and the resultant ion beam energy in a number of recent experiments. The maximum proton energy from laser-irradiated targets for experiments on different laser systems was found to be a function of the laser pulse irradiance. Laser ion power conversion efficiency (1-6%) is proportional to the laser pulse energy [47].

Apart from its fundamental research interest, laser driven ion sources can attract many applications, such as the radiography and radiotherapy [47]. Most existing medical facilities that are based on conventional ion accelerators are typically large (in size and cost), thus limiting their number and ultimately access to ion beam radiotherapy. Owing to its compactness, laser driven ion accelerators show promise for significantly reducing the size and cost of medical ion accelerators.

CONCLUSION

Lasers have been applied to accelerators for a long time. Emergent applications such as Compton scattering based high-flux light source, laser stripping, and laser driven accelerations have been made feasible owing to the rapid advancement of laser technology in the recent decade. However, to make the key factors such as the yield of X-/γ–rays, stripping efficiency, or the luminosity of the electrons stay competitive with the conventional technology, the average laser power and wall-plug efficiency have to be dramatically enhanced. Future research on the new gain medium such as the ceramic disk lasers [48], as well as a continuous effort on the beam combining technology and beam recycling optical cavity are required to meet the new challenges.

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