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CRITICAL ISSUES FOR VACUUM LASER ACCELERATION*

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Recent technological progress in lasers has renewed interest in applying high power lasers to accelerate charged particles. Outstanding gains in efficiency and power, and the first demonstration of optical phase-locking have moved the laser closer to competitive standing with microwave vacuum tubes as power sources for accelerators. We explore some of the questions that will determine the suitability of both low-field ($a_o \ll 1$) and high-field ($a_o > 1$) acceleration methods, and identify some of the challenges ahead. Possible applications include a laser-driven linear collider and novel, compact particle and radiation sources, each with its own performance requirements.

1. Introduction

The acceleration of charged particles by laser radiation has long been a dream for accelerator designers [1]. Achieving the correct conditions to permit efficient acceleration over long distances has been and remains the primary challenge in using lasers to accelerate particles. The extraordinary electric fields laser can produce make this a challenge worth pursuing.

Several applications drive the exploration of laser-driven particle acceleration. Future generations of linear colliders will be required to attain successively higher energies and higher luminosities and will place a premium on accelerating gradient, power efficiency, and the ability to preserve excellent emittances. Compact particle and radiation sources for university and industry generally operate at much lower energies and beam powers, but find a broad spectrum of applications with wide ranging requirements, hence laser accelerators built for this purpose will instead have low cost and versatility as key attributes.

A natural consequence of using optical wavelengths for acceleration is that conditions can be arranged such that the accelerated beams will be bunched at the optical wavelength. The resultant sub-femtosecond particle bunches will produce ultrafast radiation pulses that are tunable in energy, and sufficiently

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short in duration to permit the study of attosecond phenomena, such as the rearrangement of atomic electron distributions that occurs as chemical bonds are formed.

2. Coupling Mechanisms

The primary challenge in using lasers for particle acceleration is in devising means to couple energy efficiently over macroscopic distances. Efficient use of laser power requires strong focusing of the laser, making diffraction effects important. Some means to guide the laser, either with a series of focusing optics, or with a continuous waveguide is therefore required.

. The available methods for coupling radiation to charged particles are quite different depending on the strength of radiation fields. The methods divide into two groups, “low-field”, for which the normalized vector potential of the radiation $a_o=eE/2\omega mc\ll 1$ is sufficiently small that the oscillatory motion of electrons responding to the alternating optical fields remains subrelativistic, and “high-field”, for which $a_o>1$ and electrons acquire relativistic velocities during each half cycle of the optical fields. At optical wavelengths $a_o\sim 1$ corresponds to very high laser intensities, ~10^{18} W/cm^2 which, roughly speaking, is possible for lasers in the ≥30 TW class over an interaction distance of $z_R=\pi w_o^2/\lambda$~30 μm.

Generally speaking, low-field accelerators must rely on material (metals, dielectrics, gases) placed within a few wavelengths of the particle beam to sufficiently diffract the optical waves to produce an axial electric field component that has a phase velocity somewhat below the speed of light [2]. The exception to this rule is the inverse free electron laser (IFEL), which achieves synchronous interaction by bending the particle trajectories in a periodic manner such that the transverse motion permits energy transfer directly from transversely polarized fields. As such, most low-field accelerators will be limited in gradient by the voltage breakdown characteristics of the materials used, which is unlikely to exceed the atomic binding fields, ~10^{10} V/m. The interaction between fields and particles is exclusively linear in the field strength, and particles must remain in phase synchronism with the optical wave to receive continuous acceleration. Further, there is no requirement (except for the IFEL) that the particles deflect from straight-line trajectories to achieve coupling to the fields, so there is no high-energy limit to the maximum energy that can be attained.

Material damage is a key issue determining what accelerating gradients are possible. At present, energy fluences above ~2 J/cm^2 cause damage to surfaces made of fused silica [3,4], an excellent candidate material for its ease of handling by lithography and resistance to radiation damage. Crystalline materials perform marginally better, potentially due to their improved strength and thermal conductivity. The damage threshold exhibits a $\tau_p^{1/2}$ dependence on pulse length above 10 picoseconds, but is insensitive to pulse length below about 1 psec, motivating the use of very short laser pulses. For ~100 fsec laser pulses, 2 J/cm^2 corresponds to field levels approaching the atomic binding limit, 10^{10} V/m. Much can be gained by designing efficient structures that tightly couple the particles to the radiation fields, permitting lower fields on the structure surfaces for a given accelerating gradient.

The structures used to couple the particles and radiation fields will generally have geometric features at or somewhat smaller than the radiation wavelength. For laser-driven structures, this means features on the order of microns or less. Making such tiny structures with the required accuracy from materials with good optical properties is a challenge, but a similar task is accomplished by the semiconductor industry using lithographic techniques. Present UV lithography techniques can mass produce feature sizes as small as ~107 nm [5] with critical dimensions held to ±5.3 nm (3σ) in silicon and silica. Next-generation XUV lithography promises to reduce both feature size and absolute dimensional tolerances significantly. Learning the capabilities of the lithography process and the implications for structure design will be key steps to making laser accelerator structures.

For high energy physics machines, the overall power efficiency is very important. Present collider designs call for 9.6 MW of beam power (total) at the collision point, which with ~8% overall power efficiency wall-plug-to-beam requires 121 MW total AC power, which is already a significant fraction of the power output of even the largest power plants[6]. Lasers have made significant progress in total efficiency both from high efficiency pumping with diode lasers, and through the engineering of materials with very small energy differences between the pumping and lasing transitions. High power diode bars with 50% electrical-to-light efficiency are commercially available [7], with further improvement possible. Lasing media with 86.9% slope efficiencies ($Yb{:}KY(WO_4)_2$ [8], λ=1.025 μm) have already been used to make high average power lasers achieving better than 10% wall-plug-to-light efficiencies [9], with limiting efficiencies approaching 40% possible.

Strongly coupling the radiation to the particles is essential to getting good power efficiency, but strong coupling means structures must place material within a wavelength or so of the beam. The particles beams must pass through these very small holes, which presents a number of challenges. Long-range wakefields must be carefully managed with a combination of very small bunch charges and aggressive suppression of the most dangerous higher-order modes. Additionally, the beam must be kept in alignment with these tiny structures to very tight tolerances (less than an optical wavelength) over the entire accelerator length. With noise and ground motion constantly shifting the accelerator components, this will be very challenging.

High-field accelerators generally produce acceleration through the combined action of the electric and magnetic fields, with the requirement that the particles must deflect appreciably within each optical cycle to obtain strong coupling to the fields. This requirement makes accelerating very high-energy particles problematic, with the deflection resulting in rapidly growing synchrotron radiation losses with increasing particle energy. However, there is no rigid requirement that the particles remain in phase synchronism with the wave to receive acceleration. Instead, particles experience force arising from several mechanisms, including the usual first-order force, second-order $\boldsymbol{E}\times\boldsymbol{B}$ forces, and possibly higher-order terms, depending on the field intensity.

Optics must still be used to direct and focus the laser light, but may be placed many Rayleigh ranges from the interaction point, permitting a significant reduction in field strengths. As laser power grows, the optics must also grow in size and be moved still further from the focus, making the problem of obtaining sufficient surface accuracy to achieve diffraction-limited focused spot sizes rapidly more challenging.

A number of lasers exist worldwide that produce focused energy densities high enough for high-field acceleration. Many of these lasers are primarily intended for inertial confinement fusion research, but with suitable broadband seed lasers and appropriate optics, are also used for high field physics. These lasers operate in the near infrared, and are mostly optical parametric chirped-pulse amplifier (OPCPA) based systems employing large energy-storage volumes of flashlamp-pumped Nd:glass. The GEKKO XII laser at ILE Osaka [10] is a petawatt-class laser and the Vulcan laser at Rutherford Appleton Laboratory [11] will soon complete upgrades to operate at the petawatt level, with each laser storing several kilojoules of energy. The High Peak Power T^3 Laser at Jaeri-Kansai [12] is a Ti:sapphire system, and will also shortly complete upgrades to operate at the petawatt level. These kilojoule-class petawatt systems are capable, in principle, of producing fields in the $a_o{\sim}10$ range (assuming twice the diffraction-limited spot size for *f/*2 optics), making them suitable for a range of high-field experiments. Two megajoule-class facilities are under construction, the National Ignition Facility (NIF) at Livermore Laboratory [13], and the Laser

MegaJoule (LMJ) facility at CEA-Limeil [14]. These are also Nd:glass systems, which in principle could reach fields strengths beyond $a_o \sim 100$.

These megajoule class flashlamp-pumped glass lasers are very large, complicated systems, occupying several hundred square meters of floor space. They are also not power-efficient, with most of the pump power dissipated as heat in the lasing media. For the NIF and LMJ facilities, the total weight of lasing media (a glass, and hence a poor heat conductor) is over 150 tons, and consequently requires long cooling periods (8 hours for the megajoule lasers listed here) between successive shots. Ti:sapphire offers some improvement over Nd:glass both through its broader bandwidth (and hence shorter ultimate pulse lengths) and through its higher heat conductivity, but has a significantly lower saturation fluence (1 J/cm^2 vs 7 J/cm^2 for Nd:glass) requiring physically large transverse dimensions to produce high powers, is crystalline, requiring large crystals to be grown, and has a large difference between the pumping wavelength (532 nm) and lasing wavelength (800 nm), resulting in poor optical efficiency. Even so, Ti:sapphire systems offer shorter laser pulses and much higher repetition rates (e.g. 10 Hz for the Jaeri-Kansai system) making them attractive for this application. The development of better lasing media (e.g. $Yb:LiYF_4$) with high saturation fluence, good thermal properties, better efficiency, and the capability of being produced in very large, optical quality volumes will greatly improve the utility of these laser systems.

Focusing and steering such large energy laser pulses requires that very large optics (with apertures in the 1 m^2 range) be used to avoid damage. The surfaces of the optics must be accurate to produce an aberration-free focus, and hence the highest fields. Significant advances in the production of large, highly accurate, actively stabilized optics for telescopes and advances in adaptive optics have made the production of such optics possible.

3. Future Research

Rapid progress in laser technology, driven by a $5 billion/year market, has led to a number of exciting developments [15]. High power diode pumping at high efficiency is continually evolving, and offers to replace flash lamp pumping for many applications. Advances in solid-state lasing media have produced highly efficient media with good thermal conductivity that together allow very high average powers to be produced. Carrier phase locking has been demonstrated [16], a key step towards synchronizing two or more lasers at the optical level to drive multiple acceleration stages.

Experimental demonstrations of low-field laser acceleration [17] and high-field laser acceleration [18] have been made. Experiments to explore different coupling mechanisms are needed to establish the most efficient methods that are within reach of fabrication technologies. Expanded experimental efforts will be needed to understand the impact of technical issues on ultimate gradient and on the quality of accelerated beams that may be produced. Material science advances, and improvements in the accuracy with which optical components may be produced will impact both low- and high-field efforts. A handful of laboratories are pursuing experiments to explore these issues, including CEA-Limeil-Valenton, and Brookhaven National Laboratory, and two more are under construction: the Relativistic Photon-Electron Dynamics Lab at National Tsinghua University, Taiwan, and the ORION facility at SLAC.

Remarkable progress over the last decade in laser technology has brought the possibility of laser driven acceleration closer to reality. Dedicated efforts to identify and test the most promising acceleration methods, and to characterize their impact on beam quality are the next steps towards realizing the promise of laser acceleration.

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References

1. K. Shimoda, "Proposal for an Electron Accelerator Using an Optical maser," Appl. Opt., **1**, p.33 (1962) and A. Lohmann, "Electron Acceleration by Light Waves," IBM Technical Note TN5, San Jose, CA, October 3 (1962).
2. J. D. Lawson, "Laser Accelerators?," RL-75-043, (1975), but see also P. M. Woodward, J. D. Lawson, "The Theoretical Precision with which an Arbitrary Radiation-Pattern may be Obtained from a Source of Finite Size," *J. I. E. E.* **95** (III), 363, (1948), and R. B. Palmer, "A Laser-Driven Grating Linac", *Part. Accel.*, **11**, 81, (1980).
3. M. D. Perry, *et al*, "Ultrashort-Pulse Laser Machining of Dielectric Materials", J. Appl. Phys., **65**(9), p. 6803 (1999).
4. T. Plettner, "Proof-of-Principle Experiment for Crossed Laser Beam Electron Acceleration in a Dielectric Loaded Vacuum Structure", Ph.D. dissertation, Stanford University, (2002).

5. "International Technology Roadmap for Semiconductors, 2002 ITRS Update", URL: http://public.itrs.net/Files/2002Update/Home.pdf, p. 64 (2002).
6. "Zeroth-Order Design Report for the Next Linear Collider", v. I, SLAC-474, (1996).
7. *n*LIGHT Photonics, Vancouver, WA, URL: www.nlight.net .
8. Opt. Lett., **22** (17), p.1317, September (1997).
9. F. Brunner, *et al*, "240-fs Pulses with 22-W Average Power from a Mode-Locked Thin-Disk Yb:KY$(WO_4)_2$ Laser", Opt. Lett., **27**(13), p. 1162 (2002).
10. M. Nakatsuka, *et al*, "Class Laser System, GEKKO XII Upgrade for ICF Ignition", in Proc. 11th Top. Mtg. On the Tech. Fusion Energy, New Orleans, LA, June (1994).
11. C. B. Edwards, "Vulcan Petawatt Upgrade Overview", CLF/RAL Annual Report, URL: http://www.clf.rl.ac.uk/Reports/2001-2002/pdf/75.pdf (2002).
12. See URL: http://www.jaeri.go.jp/english/research/re07.html .
13. J. A. Paisner, *et al*, "National Ignition Facility Design, Schedule and Cost", in Proc. 11th Top. Mtg. On the Tech. Fusion Energy, New Orleans, LA, June (1994).
14. J. Coutant, *et al*, "The French Megajoule-Laser Project", in Proc. 11th Top. Mtg. On the Tech. Fusion Energy, New Orleans, LA, June (1994).
15. K. Kincade, "Review and Forecast of the Laser Markets", Laser Focus World, p. 73, January, (2003).
16. D. J. Jones, *et al*, "Carrier-Envelope Phase Control of Femtosecond Mode-Locked Lasers and Direct Optical Frequency Synthesis", Science, **288**, p.635 (2000).
17. W. D. Kimura, *et al*, "Detailed Experimental Results for Laser Acceleration Staging", PRST-AB, **4**, 101301 (2001).
18. P. H. Bucksbaum, *et al*, "Scattering of Electrons by Intense Coherent Light", Phys. Rev. Lett., **58**(4), p.349 (1987), P. Monot, "Energy Measurements of Electrons Submitted to an Ultrastrong Laser Field", Phys. Rev. Lett., **70**(9), p.1232 (1993), C. I. Moore, *et al*, "Observation of the Transition from Thomson to Compton Scattering in Multiphoton Interactions with Low-Energy Electrons", Phys. Rev. Lett., **74**(13),p.2439 (1995), G. Malka, *et al*, "Experimental Observation of Electrons Accelerated in Vacuum to Relativistic Energies by a High-Intensity Laser", Phys. Rev. Lett., **78**(17), p.3314 (1997).