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Summary of the 2011 Dielectric Laser Accelerator Workshop

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ABSTRACT

The first ICFA Mini-Workshop on dielectric laser accelerators (DLA) was held on September 15–16, 2011 at SLAC National Accelerator Laboratory. We present the results of the workshop, and discuss the main conclusions of the Accelerator Applications, Photonics, and Laser Technologies working groups. Over 50 participants from four countries participated, discussing the state of the art in photonic structures, laser science, and nanofabrication as it pertains to laser-driven particle acceleration in dielectric structures. Applications of this new and promising acceleration concept to discovery science and industrial, medical, and basic energy sciences were explored. The DLA community is presently focused on making demonstrations of high gradient acceleration and a compatible atto-second injector source, two critical steps towards realizing the potential of this technology.

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1. Introduction

Dielectric laser acceleration (DLA) refers to the use of optical to infrared (IR) lasers to drive high-gradient particle acceleration inside of a vacuum channel in a dielectric structure. DLA is a promising and rapidly progressing field of research and development in particle accelerator technology. The high breakdown threshold of dielectric materials at optical frequencies, relative to metals in the RF regime, makes possible significant improvements in accelerating gradient. Efficient, inexpensive, and commercially available lasers spanning a widening wavelength range can enable cost-effective accelerator systems for a variety of applications. Furthermore, the amenability of DLA structures to industrial fabrication techniques makes inexpensive commercialized mass-production a possibility. The field of DLA has achieved remarkable progress in recent years, with detailed design studies of photonic crystal and planar structures [1–4], experimental demonstration of net acceleration, and advances in fabrication techniques.

To assess the state of the field and discuss future directions, the first Dielectric Laser Accelerator Workshop was held on September 15–16, 2011, at SLAC National Accelerator Laboratory. The workshop consisted of three working groups: (1) Accelerator Applications, (2) Photonic Structures and Optical Materials, and (3) Laser Technology Requirements. While the Photonics and Laser Technology working groups were tasked with discussing particular structures and laser systems, the Accelerator Applications group was tasked with discussing how DLA technology might be applied to various types of accelerators. The applications of particle accelerators are highly varied, from small systems for medical use, where compactness and cost are of paramount concern, to high-energy colliders where accelerating gradient and power efficiency are key. The following charge was put to the working groups:

1. Identify the state-of-the-art in each field as it pertains to laser-driven particle acceleration.
2. Outline general parameters for potential industrial, medical, compact light source, and linear collider applications.
   a. Identify interface requirements between the accelerator, photonic devices, and laser systems in each case.
   b. Identify critical parameters that make or break performance in each case.
3. Identify key areas needing R&D, and sketch an R&D roadmap in each of the three subject areas.
4. Increase awareness of efforts in adjacent disciplines, identify synergies, and grow collaborations between the accelerator physics, photonics, and laser R&D communities.

2. Accelerator applications

Although DLA is a relatively new area of scientific research, the field has advanced along multiple fronts in the last few years.

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Recent work has yielded new structure designs, laser technology, injection mechanisms, fabrication techniques, experimental diagnostics, and simulation tools. There are now three distinct types of DLA structures that have been explored in detail: planar structures, which include gratings [1] and/or dielectric stacks [2]; photonic crystal fibers [3]; and three-dimensional photonic crystal structures fabricated using integrated circuit technology [4]. Efficient, short pulse lasers now exist in wavelengths spanning nearly the entire 1–2 μm range, and efforts are underway to reach longer wavelengths using parametric techniques.

The near-term goal common to virtually all projects in the DLA community is the demonstration of high accelerating gradient. In this context, high gradient means well beyond the 30–100 MV/m regime of current widely used acceleration techniques. By contrast, dielectrics have been demonstrated [5,6] to withstand electric field stresses well in excess of 1 GV/m, which is an order of magnitude higher than the breakdown limits for traditional microwave cavities. Developing accelerator structures that effectively exploit this capability will require laser systems, dielectric materials, structure topologies, and power couplers that together provide high gradient and damage threshold, while minimizing field enhancement. Several groups are experimentally exploring microtip-based electron emitters for direct injection of optically bunched beams, and we expect demonstrations of acceleration in DLA structures to occur in the 1-year time frame. It therefore makes sense to consider how current technology might scale or be integrated to achieve operational accelerator systems suitable for various types of applications. To this end, we discuss below applications for DLA in three main areas: discovery science, basic energy science, and medical science.

2.1. High-energy collider

Due to the growing cost and size of high-energy physics (HEP) facilities based on traditional RF accelerator technology, it is clear that revolutionary new accelerator concepts are needed to continue into the 10 TeV center-of-mass energy range and beyond. DLA is a particularly promising advanced concept for a future HEP collider. Example parameters for a 10 TeV collider are provided in Table 1. The three different examples ("Woodpile", "Fiber", "Grating") correspond to three different structure types under development, which are discussed in Section 3 and shown in Fig. 1. These are compared with international linear collider ("ILC") parameters scaled to 10 TeV to provide a baseline comparison against traditional RF technology. The key parameters for a DLA-based collider are gradient, wall-plug efficiency, and luminosity. Gradient is clearly critical to keep the accelerator length, and hence civil construction cost, reasonable. Since laser technology has made great strides in wall-plug-to-optical efficiency, the accelerator design requires maximizing optical-to-beam efficiency. The DLA beam power is generated by accelerating low-charge, low-emittance bunches at high repetition rate. In Table 1, the repetition rate is adjusted for the structures in order to roughly match the luminosity while keeping total wall-plug power manageable. The small beam emittances allow these bunches to be focused to the very small spot sizes needed to achieve the desired luminosity, the high repetition rates allow feedback to stabilize the beams to collide at the interaction point, and the very low bunch charge reduces the beamstrahlung loss. Indeed, at multi-TeV collider energies, a high repetition rate small bunch charge accelerator may be the only route that is sufficiently free of beamstrahlung backgrounds to be used for high energy physics.

Table 1
Strawman parameters for a 10 TeV linear collider for three DLA structures.

Parameter	*Units*	*"ILC"*	*Woodpile*	*Fiber*	*Grating*
*E*_cms	GeV	10,000	10,000	10,000	10,000
Bunch charge	e	3.0E+10	1.8E+04	3.8E+04	1.0E+04
# Bunches/train	#	2820	136	159	375
Train repetition rate	MHz	5.0E−06	25	5	10
Macro bunch length	ps	2820	1.00	0.50	0.33
Design wavelength	μm	230,609.58	1.55	1.89	0.80
Invariant emittances	μm	10/0.04	1e−04/1e−04	1e−04/1e−04	1e−04/1e−04
I.P. spot size	nm	158/1	0.06/0.06	0.06/0.06	0.06/0.06
Beamstrahlung *E*-loss	%	16.3	2.4	5.4	3.8
Enhanced luminosity	**/cm^2/s**	**1.23E+36**	**2.04E+36**	**4.09E+36**	**2.82E+36**
Beam power	MW	338.8	49.0	24.2	30.0
Wall-plug power	MW	1040.0	490.2	242.0	300.4
Gradient	MeV/m	30	197	400	830
Total linac length	km	333.3	50.8	25.0	12.0

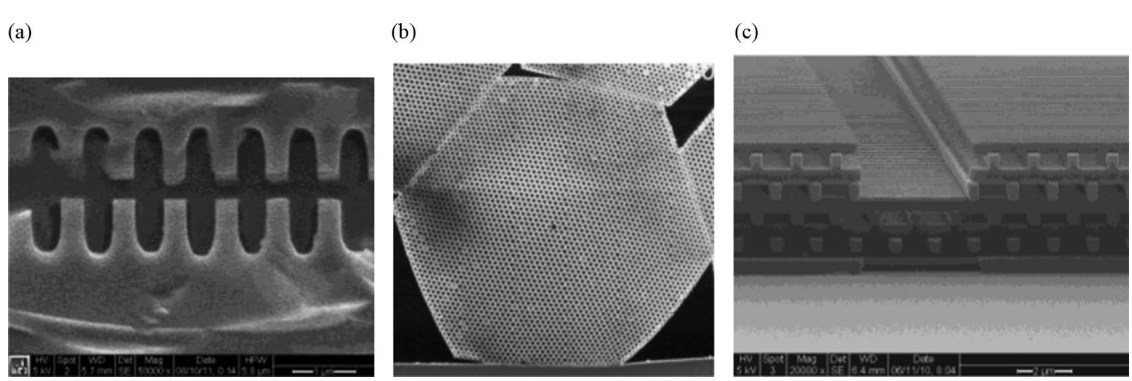

Fig. 1. Recently constructed prototypes of (a) the 1D dual grating accelerator structure with 800 nm period. (Stanford University), (b) the 2D photonic capillary wafer accelerator structure with transverse size about 700 μm (Incom, Inc.). (c) Nine-layer half structure of the 3D photonic woodpile with rectangular defect region where the particle beam traverses into the page (Stanford University).

Energy efficiency is critical due to the high beam power requirements of a linear collider. The bunch charge that can be efficiently accelerated in a DLA is limited due to beam loading to the fC level, with optimal efficiencies in the tens of percent [7]. Picosecond-scale trains of optical bunches can increase the charge to several hundred fC, but to achieve the needed average current, high repetition rates are required. Fortunately, repetition rates in the tens of MHz are well within the operating regime of fiber laser technology. With high average power mode-locked fiber lasers that have efficiencies approaching 50% expected to become commercially available on the 5–10 year time scale, future linear collider wall-plug efficiencies of 10% or higher appear reasonable. The example parameters in Table 1 assume an achievable wall-plug efficiency of 15%.

For a linear collider, the emittance must be preserved throughout the several kilometers of acceleration, so misalignments must be small enough that they do not result in significant emittance growth. In particular, it is estimated that with conventional magnetic focusing, the quadrupole alignment would have a tolerance of about 1 μm, and the accelerator structures would need to be aligned to 100 nm. Furthermore, the transverse quadrupole jitter must be below 0.1 nm. This is based on a maximum centroid motion of 10% of the beam size from magnetic center vibration, assuming 1000 quads and a normalized emittance of 0.1 nm. Jitter larger than this makes tuning challenging. For an optical accelerator on a wafer, the quadrupole focusing elements will be integrated directly with the accelerator structure as monolithic units, so these elements are by nature aligned permanently. This could potentially be done with tiny fixed-field permanent magnets or with compatible laser-driven electromagnetic focusing lenses. Schemes for making high-gradient laser-driven dielectric quadrupoles have been proposed as a variant on the fused silica dual-grating accelerator concept [22,23]. The primary challenge then becomes that of reducing inter-wafer misalignment.

A key mechanism for misalignment resulting in emittance growth is the beam break-up (BBU) instability. In BBU, transverse wakefields interact resonantly with the bunch betatron motion to drive transverse oscillations. A simple BBU model [8] was used to estimate the effect of misalignment. For 150 fC bunch train charge, it was found that a 30 nm average misalignment resulted in 2.2 nm normalized emittance growth from a cold beam over 500 GeV of acceleration in 1 km. A scan of emittance growth vs. bunch charge was conducted, and it was found that accelerating sufficient charge with tolerable beam degradation for high-energy physics applications requires about 50 nm alignment. Beam stability may be improved by using a shorter focusing period, for instance with optical focusing, as well as via BNS damping. More detailed modeling is required to evaluate mitigation strategies, and single-wafer scale experimental tests are needed. While achieving such tolerances over several km is a challenge, we note that the high repetition rate of a DLA collider provides information at MHz frequencies, which can be used for feedback stabilization, and stabilization better than 1 nm/√Hz has already been demonstrated over similar lengths scales at the LIGO facility [9].

Particle collisions with the walls of the structure pose a risk of radiation damage and formation of color centers that can change the optical properties of the materials. Some materials are more robust in this regard. Silicon dioxide and sapphire are used as insulating substrates in fabrication of radiation-hardened microchips, and also have among the highest damage thresholds for laser illumination. Laser damage studies on these and other materials have been conducted at SLAC using a HeNe probe laser to detect the onset of damage via reduction in transmissivity and/or reflectivity of the substrate during exposure to a highly focused IR beam. Similar probe techniques could possibly be used to detect onset of radiation damage in a multi-stage accelerator in order to anticipate needed replacement of individual modules. Further studies are needed to fully understand the radiation limits of these materials under very high repetition rates and with the unique electron pulse formats required for DLA operation. The effects of charge accumulation are expected to be most significant at injection (i.e. when the electrons are sub-relativistic). Deposited coatings that have small but nonzero conductivity could be used to provide a path to ground for charges that impinge on the walls of the beam channel. Investigation of fabrication processes using various materials and surface coatings, and experiments to measuring charging effects with low-energy electron beams are subjects of current study by teams at SLAC National Accelerator Laboratory, Stanford University, University of California Los Angeles (UCLA), and Max Planck Quantum (MPQ).

2.2. X-ray light sources

The development of an affordable table top x-ray light source would open new avenues of basic energy science research and make these avenues more accessible to smaller research facilities and university laboratories. Such a light source would not only benefit from the compact size of DLA devices, but would be highly suited to the production of extremely short (sub-femtosecond) light pulses, given the time structure of the electron beams produced in DLAs. The relatively smaller bunch charges in the DLA scheme lead to lower photon flux but with high brightness and brilliance; photon production may be on the order of one per electron; and photon energy is restricted by the available beam energies and device scaling. However, the high repetition rates employed in the DLA scheme could be used to compensate for the lower energy output per bunch.

For x-ray photon generation from an electron beam in the 10–100 MeV range, undulator periods would be on the order of tens of microns, making laser-driven dielectric undulator structures a natural strategy. The micro-undulator proposed in Ref. [10], which utilizes a pair of gratings transversely illuminated by a laser pulse to produce a net deflecting force on particles traveling in the vacuum channel between them, is adaptable to undulator periods from tens to hundreds of microns, and could be designed for operation over a wide range of IR wavelengths. A hard x-ray source (0.1 Å) at 1 μm wavelength would require beam injection at 2 GeV with sub-wavelength bunches. In addition, a resonant deflecting structure proposed in Ref. [11] could operate on relatively low laser power at very high repetition rate, and the interaction length would depend only on the structure; a scheme for generating the requisite 180° phase shift per undulator half-period is still under development. Both soft (60 nm) and hard (0.1 Å) x-rays could be achieved in this paradigm. The low emittances and spot sizes required for FEL operation at this scale are achievable using compact injector technology that could be micro-machined and integrated into a DLA structure. This approach is discussed in Section 3.1.

2.3. Medical devices

Given the compactness, low shielding requirements, and small beam spots of DLAs, they could be highly advantageous for a variety of medical and industrial end uses, in which low- to moderate-energy electron beams are used for direct irradiation or converted to x-rays by a bremsstrahlung target. The relatively low demands on beam quality and energy spread make this application one of the most promising for DLA-based devices.

The main parameters of interest for these applications are energy, dose rate, and irradiated volume. The most promising energy range for direct electron irradiation of tissue is 1–6 MeV, for which the stopping range is 1–3 cm (leading to minimal surrounding tissue damage). A DLA device that is contained in a millimeter-scale module could be used for cancer treatment, neuron ablation, or intracoronary radiation therapy. External beam radiotherapy could also benefit from a substantial reduction in size and cost possible with DLAs.

2.4. Summary and outlook for DLA applications

Dielectric laser accelerators hold promise for applications where high average brightness beams are required, and in each case represent a significant improvement over existing technology. These improvements strongly rely on the ability of DLA to provide high gradient, so the immediate goal is to demonstrate that gradient. A number of further technical and physics issues must be addressed for all DLA applications. The beam dynamics of a very low-charge bunch may have unique features that must be taken into account, for which further analysis and modeling is needed. Operation at very high repetition rate places demands on the drive laser as well as on structure cooling and temperature stability, both of which need study. High average power, high repetition rate lasers are available today at 1 μm wavelength. In addition, a suitable atto-second source of electrons must be completed and demonstrated. Finally, progress has been made on the efficient coupling of drive lasers into a DLA structure. Coupling for 1D structures has been tested, and coupling for 2D and 3D photonic structures will be tested in 1–2 years.

3. Accelerator structures and optical materials

Dielectric laser accelerators are designed to couple high-quality optical laser light sources to charged particles, in order to accelerate them to relativistic speeds. The methods employed generally rely upon either (1) the use of a photonic crystal medium, (2) the use of a phase mask, or a combination of both. Periodic dielectric structures, known as photonic crystals, using materials with a so-called photonic bandgap (PBG), confine light to a vacuum channel in the material, in a fashion similar to a metal waveguide [12], but with losses many orders of magnitude lower. PBGs allow for optical confinement of modes within cavities and waveguides, via the introduction of defect state(s) that break the symmetry of the crystal. Example devices include omniguides, in which a 1D photonic crystal is wrapped around into a cylinder to confine light in a hollow core [13]; 2D arrays of rods with one or more rods removed [14]; and 3D stacks of rods (known as woodpile structures) [15] or alternating rod and hole layers with one or more dielectric regions removed [16,17]. The scheme exemplified by Ref. [1] uses a phase mask instead of a photonic crystal (in this case, a pair of dielectric gratings) to produce a periodic phase reset of an incident plane wave in a vacuum region where the beam travels. Inclusion of a PBG reflector, as is proposed for the device of Ref. [27], allows for resonant confinement and enhancement of the accelerating field in the cavity.

Since the accelerating fields are restricted to a low-loss vacuum channel, dielectric laser accelerators based on these designs allow efficient coupling of laser light to charged particle beams. Developing prototype structures for testing requires simulating optimal designs, and choosing the proper materials and fabrication methods. A number of promising designs with 1D, 2D, and 3D periodicity have been proposed and were reviewed the DLA Workshop. Many of these designs are being fabricated and beam tested now or in the near future. Designs are also needed for coupling laser power to and from the accelerator waveguides.

3.1. Current state of the art in DLA accelerator design and fabrication

Several proposed DLA topologies [1,4,18] have been under recent investigation. Significant progress has been made in the fabrication of partial or full prototypes of these structures with geometries optimized for accelerator use [19,20,21] as seen in Fig. 1: (a) a structure where the beam is accelerated by a transversely incident laser beam in the gap between two gratings, (b) a glass PBG hollow-core optical fiber, and (c) a silicon "woodpile" photonic crystal waveguide.

The 1D dual grating design has been recently fabricated, in part thanks to the relatively straightforward aspect of the design [21], and initial electron beam tests are currently in progress at SLAC. The prototype shown in Fig. 1(a) has a period of 800 nm and was fabricated at Stanford University. Being made from fused silica, it is expected that these structures can sustain an acceleration gradient up to 1.2 GV/m. The field enhancement is moderate, since there is no true 3D photonic bandgap to strongly confine light to within the small aperture region. Similar structures have also been proposed for focusing, position monitoring, and deflection devices [22,23]. The 2D photonic structure of Fig. 1(b) is about a millimeter thick (drawn as glass fiber, then cut to about 1000 wavelengths sections) and is based on the holey fiber photonic crystal waveguide, in which a 2D photonic bandgap structure is turned into the transverse cross-section for a 3D waveguide. Borosilicate prototypes have been drawn for wavelengths between 1 and 7 μm. This is expected to support acceleration gradients up to 1 GV/m [24]. The woodpile structure of Fig. 1(c) is one of the more challenging structures to simulate and fabricate (due to its 3D periodicity), requiring multiple fabrication steps and sub-micron alignment. However, due to its complete 3D photonic bandgap, it can maximize the spatial and temporal confinement of laser light, allowing for relatively modest power inputs to drive gradients of 1 GV/m at 1.5 μm, approaching the damage threshold of silicon [25,26].

Two additional structures based on 1D Bragg reflecting layers have been proposed and are in development at UCLA and Purdue; these are shown in Fig. 2: (a) the micro-accelerator platform (MAP), a semi-resonant slab-symmetric structure, and (b) a 1D ominiguide cylindrical Bragg accelerator. The MAP structure of Fig. 2(a) proposed by Travish et al. from UCLA uses two distributed Bragg reflector (DBR) stacks with a vacuum defect to confine light, with a grating for input power coupling [27]. It operates in a resonant fashion which can be tuned to a desired laser wavelength by initial design, or afterwards by an electrostatic tuning mechanism between the two DBR stacks. Preliminary prototypes of this structure have been fabricated and have undergone initial electron beam testing at SLAC. The on-chip omniguide of Fig. 2 (b) represents an adaptation of the fiber-drawn omniguide structure [13], which uses an omnidirectional 1D photonic crystal rolled into a cylinder to confine light to a hollow core. The physics of its operation at wavelengths in the PBG can be understood much like traditional metallic waveguides, but with losses many orders of magnitude lower.

The low emittances and spot sizes required for these structures are achievable using compact injector technology that could be micro-machined and integrated into a DLA structure. The approach relies on field enhancement by emitting tips in a cathode region, producing micro-bunches that are then trapped in an accelerating bucket. Such micron-scale injectors would also have clear advantages for the production of extremely small beams and would be intrinsically matched to the structure. Physics studies of such emitters and their characterization are underway at various facilities, including Stanford, Vanderbilt, MPQ-Garching, and UCLA. Current experimental demonstrations of laser-enhanced field emission from nanometric tips have concentrated on the production of small, well-collimated, and ultrashort electron bunches with femtosecond or better timing precision [28,29]. To date, very low normalized emittances (about 1 nm) and high brightness have been obtained, with 10–1000 electrons per bunch using tip radii of

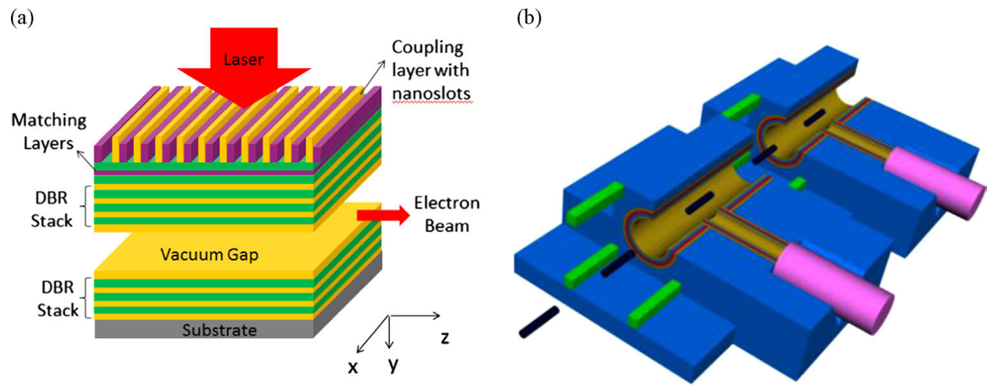

Fig. 2. Proposed structures that are in development: (a) the 1D MAP Bragg reflector accelerator structure (UCLA) and (b) the 1D omniguide dielectric accelerator. The particle beam traverses the cylindrical accelerator cavities on a path indicated by the dashed line (Purdue University).

10–100 nm. Using low-power lasers, for which repetition rates of 150 MHz or more are easily obtained, average currents can be near 100 pA. Although the bunch charges generated thus far are approximately a factor of 10 lower than what is ultimately desired for DLA, this approach appears to be a promising avenue of research for making compatible low-emittance electron sources.

In addition, the development of integrated MEMS-type diagnostics, such as beam position monitors, will be required for any DLA application to measure and control the beams. A concept for a BPM using a variant of the grating structure has recently been proposed by Soong [30]. The concept uses a dual-grating with a tapered grating period to produce a linear variation in operating wavelength along the dimension transverse to the beam axis. Light emitted by wakefield excitation by the electron beam (via the inverse of the acceleration process) would then have a different center wavelength depending on transverse position of the electrons, permitting a high-resolution measurement of beam position from the power spectrum of emitted light.

3.2. *Short-term roadmap for development of photonic crystal DLA structures*

A 10-year roadmap for DLA development is presented in Table 2. Near-term research in dielectric laser acceleration will focus primarily on demonstrating gradient in prototype structures and refining the materials and fabrication techniques for building DLA accelerator modules that can sustain the requisite laser fluence levels. This will be followed by development of second generation structures with power handling components (SOI waveguides, splitters, and efficient couplers), and design of other required accelerator components such as beam position monitors and focusing elements that are amenable to integrated MEMS and CMOS based fabrication. Once the basic principles for fabricating multi-component systems is established, a variety of applications can be explored, including portable light sources and medical sources, with the goal of producing a device capable of producing 1 GeV of net acceleration within 10 years.

Table 2
Roadmap for near-term development of DLA research.

Time scale	Anticipated developments
	Demonstrate acceleration in first-generation DLA structures Explore and test new fabrication approaches, such as: • Generation of elements by reactive ion etching • Atomic layer deposition (ALD) • Nanoimprint lithography (NIL)
1–2 years	Test novel materials for DLAs: • Sapphire, calcium fluoride • Artificial diamonds
	Develop a community computational resource: • Hardware adequate for running large simulations • Operating system suitable for a large cluster • Installed software (MEEP, MPB, VORPAL, HFSS)
2–3 years	Develop second-generation DLA structures using experimental data Simulation of all required photonic components: • Accelerator couplers and non-linear compensators • Diagnostics, focusing, and deflecting structures
3–5 years	Demonstrate photonic coupling Demonstrate techniques for avoiding deleterious nonlinear effects: • Low-nonlinearity materials • Pulse stretching and compressing
5–10 years	Demonstrate prototype portable x-ray source Demonstrate internal-beam radiotherapy source Demonstrate 1 GeV DLA electron accelerator

3.3. *Summary and outlook for photonic structures*

A variety of proposed designs were explored in the workshop, including dual gratings, 1D Bragg stacks and gratings (the MAP structure), 2D photonic crystal capillary wafers, 3D woodpile structures, and on-chip omniguides. Photonic crystals offer a promising path forward for dielectric laser accelerator systems. They provide the ability to strongly confine light, enhancing its interaction with charged particles, while limiting losses to many orders of magnitude below alternatives such as fiber optics or metal waveguides. The most significant tradeoff consideration in development of these structures was found to be between simplicity/ease of fabrication and ultimate potential performance. Prototypes of four of the five structures have been fabricated and two of these have already been tested with electron beam. Omniguides have been manufactured, but speed-of-light TM mode structures suitable for acceleration remain to be prototyped.

4. Lasers for dielectric particle accelerators

The laser requirements for a DLA based accelerator reflect the stringent power and efficiency requirements for future linear colliders as well as the unusual pulse format of the electron beam: namely very high rep rates with low per-pulse energy but high average power. In addition, because each laser pulse can drive an entire bunch train in the DLA scenario, sub-picosecond pulse lengths are not required. Below, we discuss the laser requirements, the state of the art in fiber lasers (the recommended laser technology for this application), and present a baseline design for a modular system designed to drive many stages of acceleration.

4.1. Laser requirements for a DLA based collider

The laser requirements for four examples of DLA accelerator structures are presented in Table 2, corresponding to estimated requirements for a future linear collider consistent with beam parameters and pulse format outlined in Section 2.1. For the DLA applications, the pulse envelope is of order 1 ps. Thus carrier envelope phase locking (CEP) may not be required, although the optical phase of the base carrier wave needs to be locked to the phase of the accelerating electron beam. The nominal laser type will probably be a fiber laser because of its efficiency and robust, low maintenance operation. To achieve a uniform acceleration of the electron packet, a flat top super-Gaussian pulse in time will be used to maintain a constant electric field across the pulse. Fiber lasers at 1 μm wavelengths and hundreds of Watts of average power have already been demonstrated to be capable of meeting most of these parameter requirements and higher power (> 1 kW) mode-locked systems at longer wavelengths (e.g. 2 μm thulium-doped lasers) are expected to be commercially available in the near future. Consequently, the current state of the art in laser systems is not far from what will eventually be required for large-scale accelerators based upon dielectric laser acceleration.

4.2. State-of-the-art in fiber lasers

To date only fiber laser systems truly offer the potential to attain the combination of reliability and efficiency that would be ultimately required to make a laser based particle accelerator. The beam quality of fiber lasers is typically superior compared to other lasers of similar power and pulse energy. High power fiber laser systems [31–33] leverage the waveguide properties of optical fiber in order to achieve exceptional wall-plug efficiencies (> 30%) and diffraction limited beam quality with high average output powers (> 10 kW). Pulsed fiber laser systems with pulse widths of a few nanoseconds are limited to around 4 MW peak power in a single fiber waveguide due to self-focusing [34]. This limit has been attained with 1 ns pulses and high quality beams with > 4 mJ output have been demonstrated from 100 μm-class core diameter fiber rods [35].

Ultrafast fiber lasers have demonstrated significant powers and pulse energies approaching the limits discussed with regards to nanosecond pulses above. Commercial fiber laser systems with up to 50 μJ pulse energies and sub-picosecond pulses are currently available from a number of vendors [36]. Given the current rate of development, one could reasonably expect to see mJ-class commercial systems with sub-picosecond pulses available in the next 5 years.

Recent results for chirped pulse amplification (CPA) in fiber rods have demonstrated 11 W of average power with 2.2 mJ pulse energies and > 500 fs pulses [37]. Similar rods have been employed to amplify non-stretched pulses to the 1 μJ level [38]. Systems with a very small amount of chirp (< 100 ps) have been shown to achieve a few hundred nano-joules of pulse energy in < 250 fs pulses with excellent pulse fidelity [39]. Low energy pulses have been generated via CPA using chirped volume Bragg gratings (CVBG) and attained < 200 fs pulse width, which is a promising technology for significantly reducing the size of CPA systems [40].

At present, there are two common fiber lasers that operate in the wavelength region longer than the Yb:fiber laser at 1 μm. One is the ytterbium–erbium (Yb,Er) system at around 1550 nm, the other is the 2000-nm-region Tm-doped system. The system is limited to a maximum optical efficiency of 65%, though in practice due to losses in the energy-transfer process the efficiency tends to fall in the 30–40% range. Tm-doped fibers are more promising, because it is possible to pump the Tm ions at around 800 nm, where efficient diodes are readily available. One can in theory obtain a pump-to laser efficiency of 82%. In practice, efficiencies in the 60–70% range have been obtained in multi-hundred-Watt lasers [41]. We could expect the wall-plug Tm:fiber laser efficiency to exceed 30% with careful attention paid to pump coupling and power supply efficiency.

4.3. Baseline design and options

An outline of one possible baseline design for the DLA laser system for a TeV scale accelerator is shown in Fig. 3. The design is modular to enable easy scaling to the TeV level, with timing across a long accelerator as one of the significant technical challenges. This challenge would be somewhat reduced for a 100–1000 MeV application and the design should be directly applicable to those applications as well.

The baseline design begins by producing a carrier (envelope) phase-locked oscillator with its repetition rate matched to a stable RF reference frequency source in the range of 100 MHz–1 GHz, with 1 GHz being the target. This oscillator will serve as the clock for the accelerator. The global oscillator or clock will be distributed via optical fiber to local oscillators, which are phase-locked to the global oscillator. Each structure will require a phase control loop to allow for acceleration through successive structures. Both fast and slow control of the phase will be necessary. By monitoring the energy linewidth as well as the timing of the electron bunches, successful acceleration through the structures may be confirmed.

In order to get to the pulse energy necessary per structure for TeV scale acceleration (200 nJ–10 μJ), the pulses will undergo chirped pulse amplification (CPA) [42]. The design discussed here uses dispersion control immediately following the power amplifier. In this configuration, the dispersion controller—whether it is fiber [43], grating pairs [42], chirped mirrors [44], or chirped volume Bragg gratings [45]—will set the dispersion so that after passing through the remaining elements, the pulse will be compressed to the optimal pulse length in the accelerator structure.

The baseline design looks to be a manageable system, with the toughest challenges coming from the requirements for the oscillators, the power amplifier, and the delivery optics. In addition, it will be necessary to repeat the local system multiple times, with each local system phase-locked to the global oscillator.

4.4. R&D challenges and opportunities

Power delivery and coupling to accelerator structures as well as timing issues are unique requirements for DLA. The DLA community should not expect or anticipate that these issues in particular will be solved or addressed by others and thus they are key areas for targeted R&D investments. The other areas such as kW power scaling of short pulses, compact stretchers and compressors and cost control have synergies with other laser applications. In these areas, coordination of efforts with other communities interested in development of short pulse fiber lasers would be beneficial to everyone from an overall cost perspective.

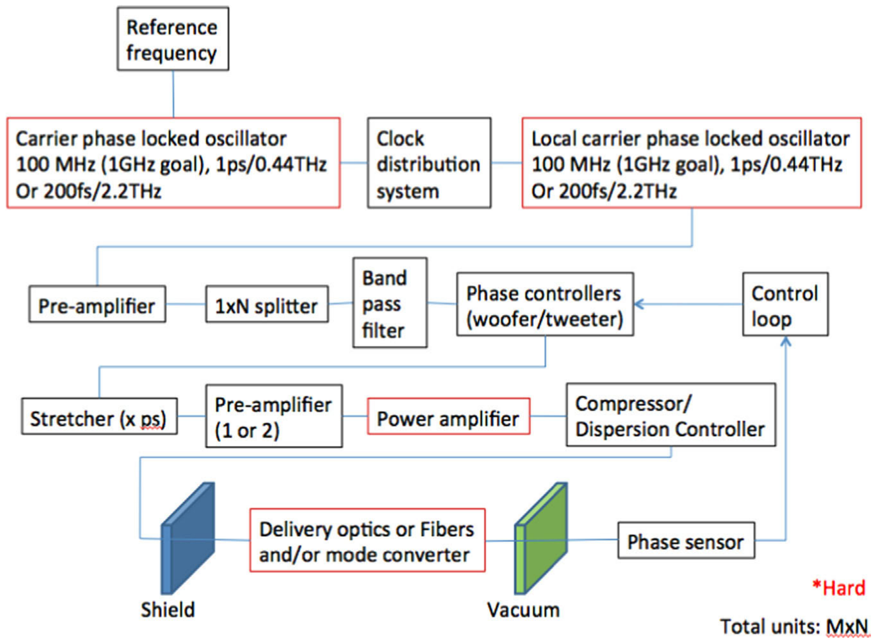

Fig. 3. The laser system baseline design is shown. The red outlined boxes highlight the challenging portions of the system. A total of M local oscillators will be built and split *N* times, giving a total of $M \times N$ laser coupled accelerator structures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.4.1. Timing issues

As the acceleration process of DLA is linear with the electric field, the optical phase must be well controlled. Poor synchronization would result in either a decrease of efficiency or an electron energy spreading or even defocusing. Frequency comb technologies can detect and control both the repetition rate of the delivered pulses and the carrier to envelop phase (CEP). The technology used to generate frequency combs in ultra-high finesse Fabry Perot cavities is able to control phase noise in the range 0.01 Hz–100 KHz. Further stabilization will necessitate control systems operating above 100 KHz and requires important efforts in feedback loops electronics as well as ultrafast ultra low noise detectors. This is a special need for the DLA application but no fundamental obstacles are foreseen.

4.4.2. Short pulses at KW average power

Depending on the accelerating technology adopted, driving lasers should deliver femtosecond pulses (from 100 fs to 10 ps) with average powers ranging between few 10 W–10 KW. For grating or resonant structures where wavelength is not restricted, Yb-doped fiber laser and amplifier technology at 1 μm is rather close to fulfilling the requirements in terms of average power, pulse energy and duration. Thulium doped materials are probably the best candidates around 2 μm, and average power in excess of 1 KW (CW operation) has been recently reported for Tm-doped fiber laser. Further research is needed to produce and amplify fs to ps pulses at such high average power in Tm-doped fibers, but this is a topic that other communities beyond DLA have an interest to solve as well.

4.4.3. Stretcher and compressor

Limiting the intensity during amplification in the fibers requires enlarging the fiber core and/or stretching the pulse in time before amplification and recompress it after in chirp pulse amplification (CPA) scheme. Dispersing optical devices are widely available at 1 μm but do not exist at longer wavelength and therefore will require specific developments. Conventional gratings, chirped volume Bragg gratings, prisms or bulk materials are expected to offer workable solutions.

4.4.4. Power delivery and coupling

Once the laser beam is generated it must be propagated to the structures and efficiently coupled into it. One can either propagate the beam in free space or in waveguides like fibers, the latter fitting better with a monolithic architecture. Lenses, windows, mirrors and standard optical elements may be used to couple free-space lasers into demonstration units, but are not likely a viable long-term solution for a many-staged device. It is therefore critical to develop integrated power delivery mechanisms using optical guided wave systems. Various proposed solutions for this include SiN, ROW, ARROW (anti-resonant reflecting optical waveguides), and optical fibers. Correction of phase drifts with optical-scale precision will also require active feedback with embedded phase correctors. Among these options, the required laser peak power can reach 100 MW (10 μJ in 100 fs) in the case of gratings and 1 MW or less for the others. Propagation of such pulses in any standard large mode area fiber will lead to pulse distortion due to excessive non-linear phase accumulation. It therefore implies that recompression of the pulses should take place at the output of the delivery fiber and just before coupling to the structure.

Coupling power into the structure efficiently is by far the biggest challenge to be addressed. Care must therefore be taken in the coupler design to avoid impedance mismatch, which would lead to localized regions of intense electric field. Initial results in simulating such couplers for the woodpile structure using silicon-on-insulator (SOI) waveguides indicate coupling efficiencies from the input waveguide to the accelerating mode close to 100% [46].

4.5. Potential game-changers

Fiber lasers have had the fortunate advantage of constantly witnessing game-changing developments. The development of ceramic gain media has resulted in a significant decrease in cost, compared to the traditional crystal gain media. Material engineering to increase the thermal conductivity of ceramic gain media is

Table 3
Laser requirements for four DLA structures, with desired parameters for a future linear collider.

Requirement	*Woodpile*	*Fiber*	*Grating*	*Resonant structure*
Pulse energy	200 nJ	1 μJ	10 μJ	1–10 μJ
Average power	200 W	1 kW	10 kW	1 kW
Wavelength (μm)	> 2	> 1	> 1	> 1
Pulse widths (ps)	1	1	0.1–0.2	1.8–10
CEP locking (deg)	< 1	< 1	< 1	< 1
Repetition rate (MHz)	100–1000	100–1000	100–1000	100–1000
Wall-plug efficiency (%)	30–40	30–40	30–40	30–40

one foreseeable future game-changer that would result in a lower price-per-watt of laser power. Similarly, material engineering to increase the doping levels of ceramics would also be an avenue to high laser power, and a potential game-changer.

For the specific application of dielectric laser accelerators, the development of a longer-wavelength fiber laser source would be a major breakthrough. While efficient high-power fiber lasers at 1 μm have already been well developed, the practical limitation of nano-fabrication (as well as laser-damage considerations for silicon) would dictate a preference to operate at a wavelength longer than 1.5 μm. Alternatively, improvements in lithography techniques (and material choices) would make current 1 μm fiber lasers a viable source and drastically change the focus of the laser development.

4.6. Laser technology outlook

The laser requirements for dielectric laser accelerators (DLA) are challenging, but are believed to be attainable without the need for revolutionary advances beyond current state of the art. The main areas of development needed to achieve the laser requirements specified in Table 2 are timing accuracy and distribution (combined with phase sensing and feedback at the point light is coupled to the electron beam), power scaling of longer wavelength fiber lasers and beam transport and coupling to the accelerator structure. Pulse energies, pulse widths and repetition rates for the DLA applications are well within what has already been demonstrated to date by fiber laser technology. Further, fiber laser technology offers a compact, robust form factor that is naturally compatible with the demanding reliability requirements for an accelerator facility. The next efforts in fiber laser technology for DLA based systems are needed in 2 μm systems, timing control, laser beam transport, and power coupling to accelerator structures (Table 3).

5. Conclusion

The field of dielectric laser acceleration has broadened to include researchers in lasers, photonic structures, and the particle accelerator community. Over 50 individuals from four countries participated in this first ICFA Mini-Workshop. An important outcome was that potential new collaborators met at this meeting and discussions for joint research began, including a new, international initiative in robust optical materials development

The Accelerator Applications group discussed the general DLA parameters for high energy colliders, compact x-ray sources, and also medical devices to treat cancer. Achieving anticipated DLA gradients of 0.3–1.0 GeV/m will revolutionize these applications in terms of compactness and reduced cost. The working group identified the low-energy micro-sources as one of the outstanding issues to be solved. Electron emitters capable of producing atto-second electron bunches with hundreds of fC per bunch are necessary for injecting particles into the accelerator. Studies are underway by at least four groups on nanotip emitters for DLA injector application. The most demanding DLA application is colliders where requirements on gradient, power efficiency, and luminously all must be satisfied. The key attribute of a DLA collider is that the beam power is obtained by accelerating low-charge, low-emittance bunches at high repetition rate. Small spots at the final focus can then be achieved and the repetition rate allows feedback to stabilize the beams. The low bunch charge reduces beamstrahlung and at multi-TeV energies this may be the only route that is sufficiently free of this background to be used for lepton colliders. DLA applications to compact x-ray sources and medical devices will probably occur sooner than the more challenging collider. In both cases electron beams of order many MeV are needed and these can be generated on single monolithic wafers, vastly simplifying the sub-micron alignment issues. A measure of the perceived importance of compact x-ray sources is the recently awarded DARPA contracts to develop compact electron accelerators and photon generators for table top x-ray machines. Within 4 years the first single wafer DLA structures for this application will come out of this program and be ready for scaling up to higher energies.

The state of the art in photonic structures and laser systems are both encouraging. Several photonic structures have already been prototyped by different researchers, and 60 MeV electron beam tests of structures have begun at the SLAC laser acceleration facility. The beam tests are intended to directly measure the achievable acceleration gradients of prototype structures during the next 1–2 years. The Photonics group identified several areas for focused research including new fabrication techniques, damage resistant materials, and photonic power couplers. The expectation is that within 5–10 years photonics structures will be developed for applications like a portable x-ray sources and a compact 1 GeV DLA electron accelerator. The Laser group came to the important conclusion that the current state of the art in laser systems is not far from what will eventually be required for large-scale accelerators based upon dielectric laser acceleration. High peak power and high average power micron-scale fiber lasers are now available, and these are almost suitable for the DLA application. The group identified important research areas for the next 5 years including reliable control of repetition rate and carrier-to-envelope phase at MHz rates, short pulse, high average power lasers, and the interface between the laser and accelerator for power delivery and coupling. The structures and laser R&D are occurring in parallel paths with several groups addressing these different topics. Although significant investment remains, there is the potential for a tremendous return in the form of compact devices for high energy physics, x-ray sources, and medical applications with smaller space requirements and orders of magnitude in cost reduction.

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