Dielectric Laser Acceleration - Letter of Interest for Snowmass 2021 Topical Group AF06 - Advanced Acceleration Concepts

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Abstract

Particle acceleration in dielectric microstructures driven by utrafast infrared lasers, or "dielectric laser acceleration" (DLA), is a rapidly evolving area of advanced accelerator research. DLA leverages well-established industrial fabrication capabilities and the commercial availability of tabletop lasers to reduce cost, with demonstrated axial accelerating fields in the GV/m range. An international effort in this area has significantly improved understanding of gradient limits, structure design, particle focusing and transport, staging, and development of compatible low-emittance electron sources. With a near-term focus on low-current MeV-scale applications for compact scientific and medical instruments, as well as novel diagnostics capabilities, the DLA approach has several key benefits that warrant consideration for future high-energy physics machines, including low beamstrahlung energy loss, modest power requirements, stability, and readiness of supporting technologies.

1 Background and Motivation

Modern state-of-the-art particle accelerators have proven an invaluable tool for scientific and industrial use. However, constraints on size and cost have inspired a variety of advanced concepts for making smaller and more affordable particle accelerators. Dielectric laser-driven acceleration (DLA) refers to the use of photonic micro-structures made of dielectric and semiconductor materials and driven by infrared lasers to accelerate charged particles [1,2]. This approach leverages available solid-state laser technology and well-established industrial fabrication methods to reduce size and cost. The use of lasers as an acceleration driver is particularly attractive, due to the intense electric fields they can generate combined with advances in the solid-state laser market toward higher power and lower cost over the last 20 years. Dielectrics and semiconductor materials are also amenable to rapid and inexpensive CMOS and MEMS fabrication methods and have damage limits corresponding to acceleration fields in the 1 to 10 GV/m range. These technological advances, combined with new concepts for efficient field confinement using optical waveguides and photonic crystals, and the first demonstration experiments of near-field structure-based laser acceleration conducted within the last few years, have set the stage for making integrated laser-driven micro-accelerators for a variety of real-world applications.

2 Current State of the Art

The DLA approach has garnered increasing interest in recent years, with a number of university, government laboratory, and industrial institutions now actively conducting research in this area. Relativistic DLA test facilities have been implemented at several institutions, including the Pegasus Laboratory at UCLA, SINBAD/ARES at DESY, and the SwissFEL beam line at PSI. Ongoing efforts include the multi-institutional Accelerator on a Chip International Program (with 6 universities, 1 company, and 3 government laboratories), Los Alamos National Laboratory, University of Tokyo, Tel-Aviv University, Technion Israel Institute of Technology, University of Liverpool, and National Tsing-Hua University.

These efforts have led to significant experimental progress over the last 5 years, including: high-gradient sub-relativistic acceleration at 220 MeV/m [3] and at 370 MeV/m [4] in silicon microstructures; high gradient (850 MeV/m) and energy gain (0.3 MeV) of relativistic electrons using femtosecond laser pulses [5, 6]; development of compatible laser-driven focusing for long-distance transport [7]; optical microbunching and net acceleration of injected beams [8, 9]; and first demonstration of an integrated waveguide coupled accelerator on a chip [10]. Compact electron sources have also been developed that utilize field emission from nanotips to produce high-brightness and low-emittance electron beams that are well suited for coupling into optical-scale devices [11]. These advances have led to working tabletop university setups that aim to produce MeV-scale electron beams [12].

3 Applications and Relevance to HEP

With tabletop DLA sources coming into operation in university labs, near-term applications that utilize presently available low-current (< 1 nA) beams with moderate particle energies in the 100 keV to few MeV range are being actively pursued. Due to the intrinsic optical-scale bunch structure, with sub-fs bunch duration, compact DLA electron sources for ultrafast science and electron diffraction studies are among the most promising applications. Compact accelerators with target energies in the few MeV range for medical dosimetry also provide a compelling near-term use for DLA technology, as highlighted in the recently released DOE Report on Basic Research Needs for Compact Medical and Security Applications [13]. Considerations for high-energy physics at the TeV scale have been outlined in the Snowmass 2013 report and several other references [1, 14] and more recently in the context of the ANAR and ALEGRO roadmaps for a future collider based on advanced accelerator technology [15, 16]. In these parameter studies, DLA meets desired luminosities with reasonable wall-plug power consumption. Key advantages include the fact that the acceleration occurs in vacuum within a fixed electromagnetic device, that the acceleration mechanism works equally well for both electrons and positrons, and that the approach is readily amenable to nanometrically precise alignment and optical stabilization. Recent optimization studies show good prospects for high gradients with increased light to kinetic energy efficiency, greatly reducing prospective power requirements [17–19]. In addition, the low-charge and high-repetition-rate particle bunch format inherent to the DLA scheme would provide a very clean crossing at the interaction point of a multi-TeV collider, with estimated beamstrahlung losses in the single percent range, as compared with tens of percents for more conventional accelerators. The highest priority challenges largely pertain to the transport of high average beam currents in the relatively narrow (micron-scale) apertures of DLA devices. In this context, focusing of the beam and the control of wake fields are of particular importance [2]. Recent studies of transport in extended structures with laser-driven focusing show good promise for charge transport, capture efficiency, and emittance preservation [7]. And proposed demonstration experiments using longer-wavelength (10 micron) laser pulses at the Brookhaven ATF facility would enable studies of multi-MeV acceleration with high charge throughput [20]. A core working group on DLA was assembled to oversee the strawman collider design and motivate relevant feasibility studies.

4 Summary

As an advanced acceleration concept, the DLA approach offers some unique advantages. The acceleration mechanism is inherently linear and occurs in a vacuum region in a static structure. In addition to the stability benefits this affords, it also means that the acceleration effect is inherently dependent on the phase of the laser field, which makes it possible to dynamically fine-tune accelerator performance by manipulation of the incident laser phase profile [6]. Axial fields of 1.8 GV/m with 0.85 GeV/m average acceleration gradients have been demonstrated [5], and wall plug efficiencies comparable or superior to conventional approaches appear quite feasible [1]. Furthermore, the primary supporting technologies (solid state lasers and nanofabrication) are already at or near the capabilities required for a full-scale accelerator based on this approach. These advantages motivate DLA research as a competitive higher gradient alternative to more conventional radio-frequency accelerators.

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