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SCALING DOWN SYNCHRONOUS ACCELERATION: RECENT RESULTS, CURRENT STATUS, AND FUTURE PLANS OF A SUBRELATIVISTIC DIELECTRIC LASER ACCELERATION PROJECT*

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Abstract

The current status of subrelativistic acceleration via optical-scale Dielectric Laser Accelerators (DLAs), with an emphasis on those developed and tested at Friedrich-Alexander University in Erlangen, Germany, is reviewed. This promising field of accelerators has demonstrated proof-of-principle results in multiple energy regimes and current efforts are moving towards developing miniaturized standalone relativistic electron sources. The near-term experiments necessary to reach this goal are detailed.

INTRODUCTION

Dielectric laser accelerators (DLAs) aim to leverage commerically available near-infrared and optical lasers and the well-developed field of dielectric nanofabrication to accelerate charged particles with gradients approaching 10 GeV/m [1]. DLAs operate under the same principle of synchronous acceleration employed by numerous RF linear accelerators worldwide and first theorized by Wideroe in 1928 [2]. This principle was adapted towards laser-use via inverse Smith-Purcell radiation [3] and inverse Cherenkov radiation [4] in the 1960s and the idea of introducing dielectrics was conceived in the 1990s [5, 6]. The field gradients from commerically available lasers and the breakdown thresholds of candidate DLA materials allow DLAs to both scale down in size and scale up in field gradient in comparison to their RF brethren [7].

Recent experiments have demonstrated the principle of dielectric laser acceleration of both subrelativistic (30 keV [8] and 100 keV [9]) and relativistic (60 MeV [10]) electron beams. The demonstration of acceleration of 30 keV electrons in Erlangen is documented in detail here. The future directions of the Erlangen DLA project, aimed towards development of a miniaturized standalone relativistic electron source, are then outlined.

THE SINGLE GRATING DLA

The specific geometry used to accelerate 30 keV electrons is the 'single grating DLA', a fused silica phase mask with grating teeth of periodicity on the order of the incident laser wavelength. It has been designed, fabricated and tested. A cross-section of this fused silica grating mask along with the longitudinal electromagnetic fields (of the accelerating mode) excited when the grating is struck by an incident laser, is shown in Figure 1. Although Figure 1 displays the third harmonic field pattern excited by the incident laser, all harmonics of this fundamental mode are excited, each with a phase velocity of $\frac{c\lambda_p}{n\lambda}$ where c is the speed of light, λ_p is the periodicity of the single grating, n is the order of the harmonic, and λ is the central wavelength of the incident laser. As described above, synchronous acceleration occurs if and only if the phase velocity of one of the excited harmonics matches the velocity of electrons traversing the near-field profile above the grating (travelling from left to right in Figure 1).

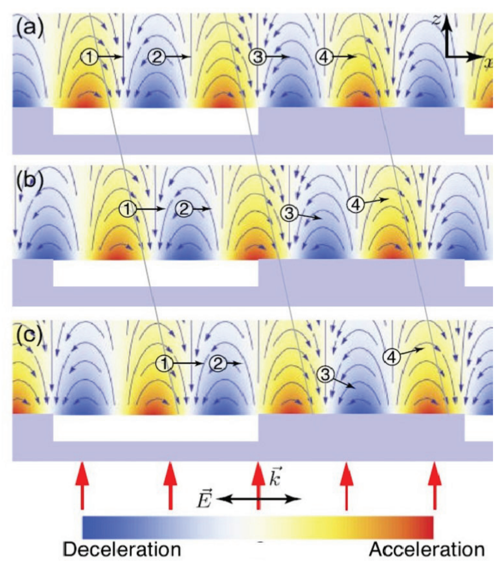

Figure 1: Three consecutive snapshots in time of the evolution of the third harmonic of the excited fields along with the evolution of four different injection phases corresponding to acceleration (1), deceleration (2) or deflection (3,4).

Two features of the field patterns in Figure 1 are of note (and described in more detail elsewhere [11]): 1) for an electron beam that samples all phases of the accelerating mode (such as the beam used in the experiment described below), half of the electron beam will see accelerating fields whereas half will see decelerating fields, and 2) only those electrons that are injected within the transverse evanescent decay length of the accelerating mode (within 200nm of the grating surface in the below experiment) will traverse fields of significant magnitude. The latter of these conditions then requires that the electron beam must be aligned to within 200nm of the grating surface. However, clipping of

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the electron beam on either the grating or the surrounding substrate on which it is fabricated would result in deflection away from the sample and the strong accelerating fields. To prevent this clipping, the grating is fabricated on top of a mesa geometry and the grating and surrounding substrate are coated in a thin metal layer to prevent charging. More details of this design, as well as the fabrication of the grating and mesa, are given in Reference 8.

EXPERIMENTAL SETUP

An electron beam ideally suited for the single grating DLA experiments must have a spot size smaller than the transverse decay length of the accelerating mode field profile and an emittance low enough to traverse the laser spot size without significant divergence. The DC electron beams generated by thermal emission scanning electron microscopes fit this purpose well. For the single grating DLA experiment, a Hitachi SEM column was used, with a variable (user-controlled) energy ranging from 0 to 30 keV, a transverse spot size of 70nm in focus and a current of 3 pA. As these electrons travel above the single grating DLA, it is illuminated by a long-cavity oscillator Ti:Sapphire laser, with a central wavelength of 787 nm, a pulse length of 110 fs, a spot size of 9 um x 9 um, a pulse energy of 150 nJ and a repetition rate of 2.7 MHz. The fused silica grating itself is fabricated by a combination of UV lithography and reactive ion etching and is 25 um long in the direction of electron propagation. The combination of the relatively low DC current electron beam and short pulse length/low repetition rate of the laser implies that only 10-15 electrons interact with laser pulses each second. The detection scheme employed in this experiment needs to be extremely sensitive and with a very low noise level. To achieve this, a combination of a retarding field spectrometer (to filter out decelerated and noninteracting electrons), bending coil and beam block (to reduce the background signal from photoelectrons), and micro-channel plate (MCP) were used. The setup is summarized in Figure 2.

RESULTS

To search for an acceleration signal, correlation in timing between the MCP signal and the arrival time of a picked-off part of the laser pulse at an avalanche photodiode (APD) upstream of the experimental chamber was examined. The electronic setup of this detection scheme is given in Figure 3.

As seen in Figure 3, a spike in the MCP signal above noise level was found consistently at a 330 ns delay after the APD signal. By examining the strength of this integrated MCP signal as a function of retarding field spectrometer voltage, incident laser polarization, electron velocity, and electron-beam-to-grating-surface distance, it was inferred that this signal in fact corresponded to those electrons accelerated by the diffracted fields described above [8]. A maximum acceleration gradient of 30 MeV/m has since been observed, matching well with simulations [11].

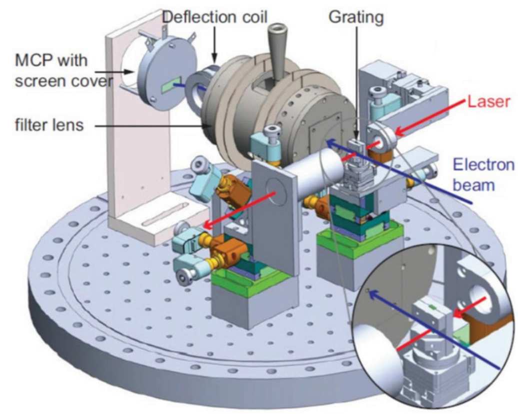

Figure 2: A schematic of the vacuum chamber used in the Erlangen DLA project. This includes the thermal emission SEM column electron source, the single grating DLA on na actuator stage, a final focusing lens for the incident laser, a microscope objective for viewing the sample from outside of the chamber, a retarding field spectrometer and a micro-channel plate detector.

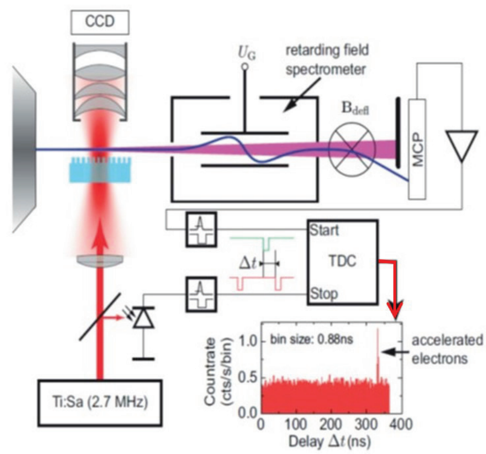

Figure 3: The coincidence circuit used to detect a correlation in the integrated MCP count rate with the arrival time of the laser pulse.

Other DLA Results

In addition to the proof of principle demonstration of dielectric laser acceleration of subrelativistic electrons in Erlangen, experiments exhibiting the viability of DLAs have shown successful results elsewhere. In SLAC, acceleration of 60 MeV electrons via a double grating structure with field gradients approaching 300 MeV/m has been demonstrated [10] while at Stanford, acceleration of 100 keV electrons via a single grating Si structure with gradients exceeding 300 MeV/m has been shown [9]. Other structures, including PBG waveguides [12] and resonanating dielectric cavities [13] have been tested for acceleration as well. We aim to build upon these results to develop an electron gun/ accelerator that accelerates electrons from 30 keV up to 1 MeV or higher using DLAs. The small footprint of such a de-

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vice enables many novel applications, including nanosurgery tumor irradiation, miniaturized cathode ray tubes, and table top sized FELs.

FUTURE DIRECTIONS

With proof-of-principle DLA-based acceleration of sub-relativistic and relativistic electrons already shown, current efforts in Erlangen are focused on improving various aspects of the previous experiment,with the goal of developing and proving the viability of a scaled-up multi-stage DLA. A hypothetical sketch of such a multi-stage DLA is shown in Figure 4.

In order to move towards realizing the envisioned multi-stage DLA (MSDLA), the acceleration efficiency of DLAs must be optimized, the ability of DLAs to accelerate electrons with increasing velocities must be demonstrated, focusing and deflecting structures must be proven effective, and a laser-triggered electron source must be effectively incorporated with the MSDLA. Experiments are underway in Erlangen to achieve each of these objectives, described below.

Electromagnetic Source

The hypothetical efficiency of DLAs has been analytically treated and is expected to approach 0.5 (the ratio of accelerating gradient to peak incident gradient) [14]. In order approach this efficiency experimentally, simple upgrades to the optical setup of the laser have already been installed. A cylindrical telescope has been installed upstream of the experimental chamber to change the laser spot to an elliptical 9 um x 2 um spot aligned to the propagation axis of the electron beam. In this fashion less of the laser energy is wasted around the sides of the electron beam. Further, a dispersive grating has been installed to provide a pulse front tilt to the incoming laser (i.e. an angle has been introduced between the intensity and pulse fronts of the laser [15]). By controlling the angle of the pulse front so that the accelerated electrons traversing the illuminated grating always see the maximum intensity front of the laser, the total energy gain, and thus acceleration efficiency, can be increased. Moreover, a Thulium fiber (with a central wavelength of 2 um) will soon be used as a replacement/upgrade to the Ti:Sapphire laser described above. Using a 2 um laser allows for larger structure periodicity, fabrication of a Si structure (thus leveraging the well-developed Si fabrication industry), and the ability to use the fundamental harmonic of the diffracted laser field pattern, thus increasing the efficiency of acceleration.

Two Stage Acceleration and Focusing

To move towards a multi-stage DLA, it is first necessary to show that a 2-stage DLA is feasible. However, as the velocity of electrons is increased via acceleration over longer distances, the synchronicity condition between the electrons and a fixed phase velocity accelerating mode is soon lost. To maintain synchronicity, the phase velocity of the accelerating mode must be increased, either continuously or discretely. In our two stage acceleration experiment, the structural period of the second DLA stage, λ_{p2} is larger than the structural period of the first stage of the grating λ_{p1}, thus increasing the phase velocity discretely between the two stages. Particle tracking simulations have demonstrated the total energy gain of accelerated electrons passing above the 2-stage single grating DLA illuminated by a single laser pulse split into two by a beamsplitter is higher in the case where $\lambda_{p2} > \lambda_{p1}$ as compared to the case where $\lambda_{p2} = \lambda_{p1}$, as is shown in Figure 5.

We note here that the intended increase in phase velocity of the accelerating mode can also be achieved by a continous growth in the structural period of the grating as well as by introducing a chirp to the incident laser pulse. Both of these avenues are also being investigated. In addition to testing a 2-stage tapered DLA structure, we intend to incorporate a focusing element, using the focusing fields of the double grating structure [17]. By keeping the accelerated electrons collimated while they traverse the accelerating modes of multiple stages, a larger fraction of electrons will in fact be accelerated.

Particle Source Upgrades

As detailed above, the electron source used in the previous single grating DLA experiment is a thermal emission DC SEM column. However, a DC source is not well suited to a compact multi-stage DLA. On the other hand, a laser triggered source would be much better suited as one could use the same laser to generate electrons and to later accelerate them. Work is currently underway to find a suitable electron source for the MSDLA. Previous analytical and numerical work in Reference 11 has placed an upper limit on the peak current achievable in the double grating DLA. In this analysis, we assume a 100 nm radius electron beam with an energy of 30 keV traversing 10 GV/m fields. By limiting the magnitude of the perveance term in the emittance-dominated paraxial ray equation (thus treating the space charge effect as a perturbation) a maximum peak current of .2 mA is found. For larger currents, space charge effects fundamentally alter the dynamics, leading to spot size growth and beam loss. However, by using a ribbon beam instead of a circular beam (the latter is assumed in the above analysis) the peak current can be increased. To realize such currents, many potential sources are under investigation. Field emission tips (such as those in transmission electron columns) will provide electron beams with sufficiently low emittance (on the nm-rad scale), but it has not yet been shown that these beams will have sufficient current for interesting applications (approaching nA for a MHz triggering laser). Although previous work has shown that obtaining 2000 electrons per laser pulse is achievable [16], reaching such emission levels with the lasers used in the DLA project (the Ti:Sapphire and Thulium lasers described above) has proved challenging, likely due to their longer pulse lengths. Thus, the applicability of field emission tips (as well as other potential photocathode sources) for DLA work requires further study.

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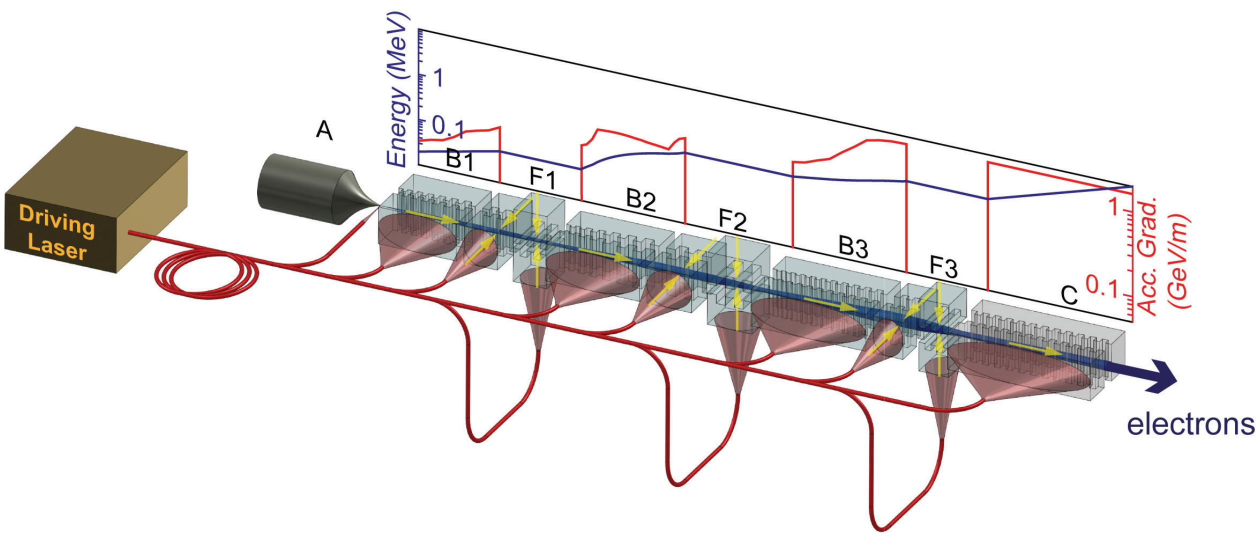

Figure 4: A schematic of an envisioned multi-stage DLA based accelerator. This includes a laser-triggered electron source, subrelativistic accelerating and focusing elements, a fiber-based laser power distribution network, and relativistic focusing and accelerating elements.

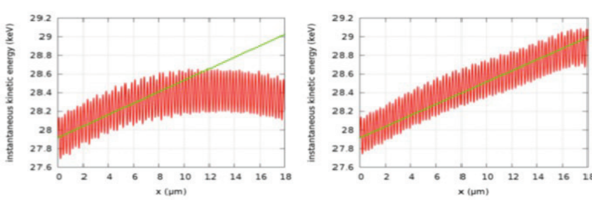

Figure 5: Simulated electron kinetic energy as a single electron travels above the surface of a two-stage DLA. On the left, the structural period of the two stages is the same, whereas on the right, $\lambda_{p2} > \lambda_{p1}$. The short-scale energy oscillations here are due to interactions with non-synchronous diffracted modes near the surface of the single grating DLA; the net energy gain is due to interaction with the synchronous accelerating mode.

CONCLUSIONS

DLAs have proven to be effective means of charged particle acceleration in both the subrelativistic and relativistic regime. Current work is focused on developing the components/properties necessary for the realization of a MSDLA, including but not limited to acceleration efficiency optimization, focusing, multi-stage acceleration, and a laser-triggered incorporated electron source. High brightness beams will allow reaching peak currents in the mA range and average currents in the nA range, but much development is needed to control these sub-micron electron beams.

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