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Recent Experimental Results and Future Directions of the DLA Single Grating Project

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Abstract. The recent demonstration of Dielectric Laser Acceleration of subrelativistic electrons is reviewed. In this experiment, a Ti:Sapphire laser is incident upon a fused silica grating, exciting fields that accelerated 28 keV electrons with a 25 MeV/m acceleration gradient. Upgrades and future directions of this DLA project are discussed.

INTRODUCTION

In order to test the viability of Dielectric Laser Accelerators (DLA's) in the subrelativistic regime, an effort to verify the acceleration of 28 keV electrons near a fused silica grating mask struck by an incident Ti:Sapphire laser has been ongoing in Garching (previously) and Erlangen (currently). A cross-section of the fused silica grating mask previously tested, along with the longitudinal electromagnetic fields excited when the grating is struck by an incident laser, is shown in Figure 1.

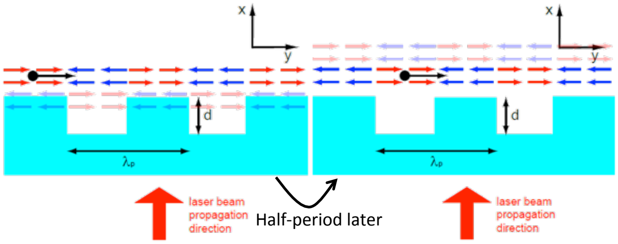

FIGURE 1. Two snapshots of one period of the cross-section of the single grating DLA. An incident laser is incident upon the grating from the $-x$-direction and after traversing the glass grating, forms the diffracted field pattern represented by red (accelerating) and blue (decelerating) arrows. Electrons traverse the fields in the $+y$-direction. λ_p is the grating periodicity and d is the grating depth.

Any mode excited by the diffraction of the incident laser via the single grating that has a phase velocity matching the electron velocity can synchronously accelerate electrons traversing the grating surface. The synchronicity condition required for net acceleration is given in Equation 1, in which λ is the wavelength of the incident laser, β is the ratio of the electron velocity to the speed of light and m is the order of the synchronous harmonic.

$$\lambda_p = m\beta\lambda \tag{1}$$

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In the experiment previously conducted, this synchronicity condition was met with λ_p =750nm, λ =787nm, β=0.3, and m=3. Acceleration was recently observed in this experiment led by John Breuer in Garching. Although described fully elsewhere [1], the setup and results of this experiment are now briefly summarized.

PREVIOUS RESULTS

The source of electrons used in this experiment is a DC thermal-emission SEM column. The electrons emitted by this column have a variable (user-controlled) energy ranging from 0 to 30 keV, a transverse spot size of 70nm and a current of 3 pA. The electrons traverse a single grating DLA that is illuminated by a long-cavity oscillator Ti:Sapphire laser. The laser has a central wavelength of 787 nm, a pulse length of 110 fs, a spot size of 9 μm x 9 μm, and 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 [1] and is 25 μm 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 per second cross the grating while it is illuminated. As a result, the detection scheme employed in this experiment needed 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 electrons), bending coil and beam block (to reduce the background signal from photoelectrons), and micro-channel plate (MCP) were used. The entire setup is summarized in Figure 2.

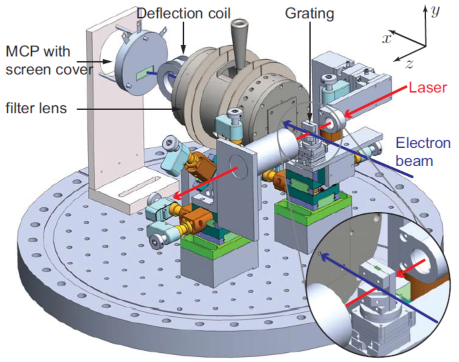

FIGURE 2. The inside of the experimental chamber. The electron beam is generated by a SEM column (not shown) and traverses the grating, sitting on an actuator stage and illuminate by a Ti:Sapphire laser., and then passes through a retarding field spectrometer, is bent around a beam block by a deflection coil, and finally reaches a micro-channel plate.

By examining the correlation in timing between the MCP signal and the arrival time of the laser pulse at an avalanche photodiode (APD) upstream of the experimental chamber, a spike in the MCP signal above noise level was found consistently at a 300 ns delay from the APD signal. From a series of measurements, this signal was deduced to be an acceleration signal. A maximum acceleration gradient of 25 MeV/m was observed [1], matching well with simulations [2].

FUTURE DIRECTIONS

Current efforts are focused on improving various aspects of the previous experiment, including but not limited to:

- The laser source and related optics;
- The geometry and composition of the DLA sample; and,
- The electron source.

Laser and Optics Upgrades

In order to improve the efficiency of acceleration (i.e. the percentage of laser pulse energy that is converted into electron energy gain), 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 μm x 2 μm 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) [3]. 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 [4].

Additionally, plans are in place to install a thulium fiber laser (with a central wavelength of 2 μm) in the place of the current Ti:Sapphire laser. Using a 2 μm laser allows for larger structure periodicity (see Equation 1), 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.

DLA Geometry Upgrades

To move towards a multi-stage DLA, it is first necessary to show that a 2-stage DLA is feasible. However, as one increases the interaction distance between the electrons and diffracted laser fields, dephasing due to deceleration must be taken into account. Indeed, as the β in Equation 1 is increased, the synchronicity condition is soon not met. In the experiment described above, the distance over which an electron dephased was from an accelerating phase to decelerating phase was calculated to be 9 μm. In order to have multi-stage acceleration over a distance longer than this, this dephasing needs to be compensated for via structure tapering. That is, the second stage of the grating structure must have a longer periodicity than the first, to match the increased electron velocity of accelerated electrons. A sketch of this geometry is given in Figure 3.

FIGURE 3. A sketch of the 2-stage tapered DLA geometry. Electrons travel from left to right above 2 single grating sections with distinct grating periodicities λ_{p1} and λ_{p2} with $\lambda_{p2}>\lambda_{p1}$

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 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 4.

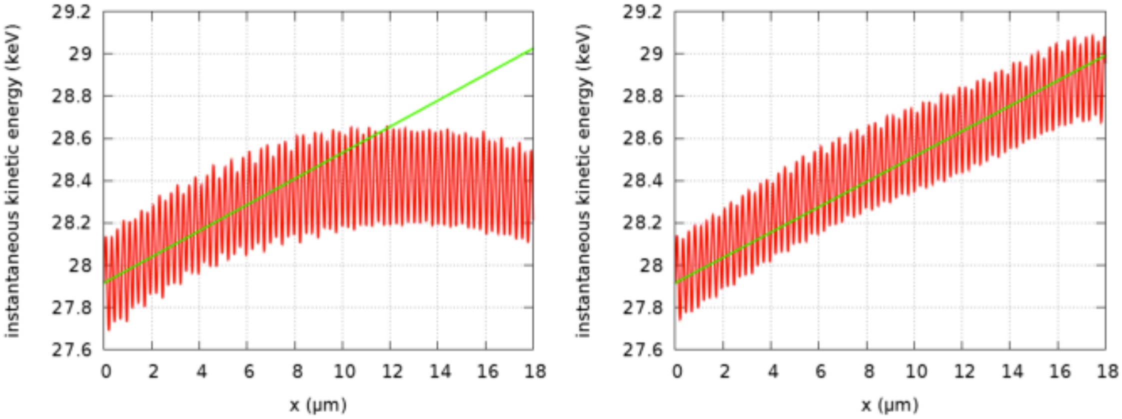

FIGURE 4. The energy gain of accelerated electrons 100 nm above the surface of the 2-stage DLA described above. On the left, $\lambda_{p2}=\lambda_{p1}$, whereas on the right, $\lambda_{p2}>\lambda_{p1}$. Dephasing at ~9 μm is avoided in the latter case.

In addition to testing a 2-stage tapered DLA structure, the double grating DLA (described extensively elsewhere [4, 5]) will be tested in the subrelativistic experimental chamber described above. The excitation efficiency of the synchronous accelerating mode is improved for the double grating in comparison to the single grating, thus improving the acceleration efficiency.

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 develop the focusing and steering electromagnets for a 100 keV field-emission gun. By illuminating the tungsten needle tip with a focused laser, we hope to laser-trigger the emission of electrons. Eventually, this source will be added to the experimental setup in Figure 2.

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