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Direct laser acceleration of 28 keV electrons at a single dielectric grating

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Abstract

Direct laser acceleration exploiting the large optical field strength of short laser pulses and the proximity of a dielectric structure can support high acceleration gradients and may therefore lead to much smaller accelerators, with potential application in table-top free electron lasers. We report a proof-of-concept experiment demonstrating direct laser acceleration of non-relativistic 28 keV electrons derived from a conventional scanning electron microscope column at a single fused-silica grating. The electrons pass the grating as closely as 50 nm and interact with the third spatial harmonic, which is excited by 100 fs Titanium:sapphire laser pulses with a peak electric field of 2.85 GV/m. The observed maximum acceleration gradient of 25 MeV/m is already comparable to state-of-the-art RF structures. This work represents the first demonstration of scalable laser acceleration and of the inverse Smith-Purcell effect in the optical regime.

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1. Introduction

Today’s linear accelerators are based on radio-frequency-driven (RF-driven) metal structures that can accelerate electrons with acceleration gradients around 20-50 MeV/m. Acceleration structures with a maximum acceleration gradient of \(~100\) MeV/m have been tested \cite{1–3}, close to the limit given by RF breakdown phenomena due to the large electric fields at the metal surfaces \cite{4}. Compared with metals, dielectric materials can sustain up to two orders of magnitude larger surface electric fields in the optical regime \cite{5}. Therefore dielectric laser accelerators are expected to provide acceleration gradients above 1 GeV/m owing to the larger damage threshold of the dielectrics as well as the large optical field strength of short laser pulses \cite{6, 7}. This may lead to a new kind of optical accelerators that are up to a factor of 100 smaller, and hence also more economical, than conventional accelerators.

In our experiment we accelerate non-relativistic 28 keV electrons in the near-field of a fused silica grating structure using the inverse Smith-Purcell effect in the optical regime. Our structures are directly compatible with the ones used in the parallel demonstration of dielectric laser acceleration of relativistic 60 MeV electrons by our collaborators

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Fig. 1. Conceptual picture of the grating-based electron acceleration. The field distribution of the third spatial harmonic is shown (color-coded). It is excited by a laser which is polarized in the plane of drawing (electric field $\vec{E}$) and incident on the transparent grating (light blue structure) from below. The grating period is $\lambda_p$. Electrons (black dots) passing the grating surface with a velocity $v = \beta c = c \lambda_p / (3\lambda)$ are synchronous with the third ($n = 3$) spatial harmonic. Depending on their relative position inside the field, they can experience either acceleration (1), deceleration (2) or deflection (3,4).

at SLAC [8]. Hence, both results together demonstrate the feasibility of a scalable concept of laser-driven particle acceleration.

2. Theory and simulation

Electron acceleration with oscillating fields requires an electromagnetic wave that has a phase speed which is equal and parallel to the electron’s velocity. Such modes can exist close to periodic grating structures. An electromagnetic wave, which oscillates with an angular frequency $\omega_0$ and impinges onto a grating of period $\lambda_p$, excites evanescent modes, also known as spatial harmonics. These spatial harmonics fall off exponentially away from the grating surface and have a phase velocity $v_{ph} = \omega_0 \lambda_p / (2\pi n)$, with the spatial harmonic’s order $n = 1, 2, 3, \ldots$. Electrons passing the grating surface at a velocity $v_e = \beta c$, with $c$ the speed of light, travel synchronously with the spatial harmonic as long as $v_e = v_{ph}$. This yields the synchronicity condition [9, 10]

$$\lambda_p = n \beta \frac{2\pi c}{\omega_0} = n \beta \lambda, \quad (1)$$

with the incident wave’s wavelength $\lambda$.

Figure 1 shows a conceptual picture of an electron passing the grating surface and interacting with the third spatial harmonic, as used in the experiment. The field falls off exponentially with increasing distance from the grating surface. Hence, electrons have to pass within a fraction of the wavelength to experience the synchronous mode. Depending on the position of the electron with respect to the field, it can be accelerated, decelerated or deflected. The force exerted onto the electron by other asynchronous spatial harmonics averages to zero over time.

We have simulated the excitation of the near-field of a fused silica grating structure with an eigenmode expansion method [11]. Thereby we obtain the field amplitude of the synchronous (third) spatial harmonic as a function of the incident laser’s peak electric field $E_p$. In Figure 2 we show the results of a particle tracking simulation of 28 keV electrons inside the near-field of the fused silica grating used in the experiment. The experimental parameters used for this simulation are discussed below. Figure 2 shows the exponentially decaying energy gain with increasing distance from the grating surface, which agrees with the theoretical predictions. Depending on their initial phase, electrons
Fig. 2. Results of particle tracking simulation of single 28 keV electron inside the near-field of the fused silica grating ($\lambda_p = 750$ nm) used in the experiment. The exciting laser pulse has a center wavelength $\lambda = 787$ nm, a pulse duration $\tau_p = 110$ fs, a focal waist radius $w_0 = 9$ $\mu$m and a peak electric field $E_p = 2.85$ GV/m. We show the simulated energy gain as a function of the initial distance of the electron from the grating surface and of the initial phase, which is directly connected to the relative position of the electron inside the field. The white areas correspond to initial parameters for which the electron gets deflected into the grating surface during the simulation.

become accelerated or decelerated. The white areas indicate that the majority of electrons passing the grating closer than $\sim 50$ nm become deflected into the grating. We expect that electrons which pass the grating at a distance of 100 nm gain $\sim 100$ eV in energy. This, together with the interaction distance of 11 $\mu$m, corresponds to an acceleration gradient of 9 MeV/m.

3. Experiment

As an electron source we use the column of a conventional scanning electron microscope that provides the well-controllable 28 keV electron beam ($\beta = 0.32$) with a DC beam current $I_b = 4$ pA and a focal waist radius of $\sim 70$ nm. We use laser pulses derived from a long-cavity Titanium:sapphire oscillator to excite the near-field of the grating [12]. The laser parameters are: center wavelength $\lambda = 787$ nm, pulse duration $\tau_p = 110$ fs, repetition rate $f_{rep} = 2.7$ MHz, focal waist radius $w_0 = 9$ $\mu$m and laser peak electric field $E_p = 2.85$ GV/m.

The experimental setup is schematically depicted in Figure 3 (a). The electrons pass the grating structure and interact with the near-field of the grating. Afterwards, the electrons’ energy is analyzed with a spectrometer. The grating with a grating period $\lambda_p = 750$ nm is located on top of a mesa structure to allow a close approach of the electron beam without clipping at the substrate (Figure 3 (b)). Hence, the electrons can pass the grating at distances below 100 nm and synchronously interact with the third spatial harmonic, as $\beta = \lambda_p/(3 \lambda) = 0.32$. By preventing beam clipping at the fused silica substrate, the mesa also reduces surface charging of the glass surface that would lead to beam deflection.

The electron beam enters a retarding field spectrometer that blocks all unaccelerated electrons. A microchannel plate detector is used to detect the accelerated electrons that can pass the spectrometer. The number of electrons that can interact with the laser pulses is $\sim f_{rep} \tau_p I_b = 10$ electrons per second. Due to this relatively low expected count rate, we electronically detect coincidences between the detector counts and the laser pulse arrival time measured by a photodiode.

With this detection scheme we are able to measure a maximum acceleration gradient of 25 MeV/m, already comparable to state-of-the-art accelerator facilities. Further measurements confirm the acceleration via the inverse Smith-Purcell effect and show good agreement with our simulations. The measurement results are published elsewhere [13].
Fig. 3. (a), Artist’s conception of the experimental setup. An electron column (left) from a conventional scanning electron microscope provides the electrons (blue) which pass the grating (center) surface and interact with the near-field excited by laser pulses (red) from below. After the interaction the electrons enter a spectrometer (right) which measures their energy gain. (b), Scanning electron microscope image of the fused silica grating that is structured on top of a mesa. The grating period is 750 nm. The mesa is 25 μm wide and 20 μm high.

4. Conclusion

In this proof-of-concept experiment we have demonstrated the inverse Smith-Purcell effect in the optical regime. We have measured a maximum acceleration gradient of 25 MeV/m at a scalable grating structure. The inter-compatibility of our scheme with the recent demonstration of relativistic electrons [8] bolsters the vision of all-optical accelerators. In these novel devices the non-relativistic structures can be used as a part of the electron injector to accelerate electrons from a low-emittance electron source to relativistic energies at optical frequencies.

Next important steps include the combination of the acceleration structures with a pulsed electron source as well as the demonstration of acceleration over longer distances, which will require grating-based focusing structures to counteract beam divergence [9]. The design of a high-brightness electron source that can operate synchronously with optical acceleration structures is reported in [14].

Applications of dielectric laser accelerators providing ultralow-emittance electron beams at repetition rates in the MHz to GHz regime may result in future compact free electron lasers [15]. This would have a great impact across all disciplines by offering smaller and more economical sources of coherent X-ray radiation to a broad community of users. Further applications may result in novel electron optical devices that can be used in ultrafast electron diffraction experiments or time-resolved electron microscopy.

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