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Spatio-Temporal Coupling Controlled Laser for Electron Acceleration

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Limited by the difficulty in acceleration synchronization, it has been a long-term challenge for on-chip dielectric laser-based accelerators (DLA) to bridge the gap between non-relativistic and relativistic regimes. Here, we propose a DLA based on a spatio-temporal coupling (STC) controlled laser pulse, which enables the acceleration of a non-relativistic electron to a sub-MeV level in a single acceleration structure (chirped spatial grating). It provides high precision temporal and spatial tuning of the driving laser via dispersion manipulation, leading to a synchronous acceleration of the velocity increasing electrons over a large energy range. Additionally, the STC scheme is a general method and can be extended to driving fields of other wavelengths such as terahertz pulses. Our results bring new possibilities to MeV-scale portable electron sources and table-top acceleration experiments.

I. Introduction

Particle accelerators have attracted a lot of interest over the past years ranging from medical imaging, therapy and fundamental sciences [1, 2]. Radio frequency (RF)-powered devices are the conventional choice for the accelerating elements [3]. However, its large size, high input power and costly infrastructures limit its utility and accessibility to broader scientific communities. The growing desires for on-chip accelerations, portable medical devices, and radiotherapy machines motivate us to explore alternative technologies that are more compact and cost-effective [4–6]. Recently multiple small scale novel accelerator concepts have been shown, such as laser-plasma accelerators, terahertz-driven accelerators and dielectric laser accelerators. Dielectric-laser accelerators (DLAs) [5, 7] powered by femtosecond lasers is another promising option, owing to the high damage threshold in the dielectric material [8], modern ultrashort pulse lasers, and nanofabrication technologies [9]. It supports a few GV/m [10] field gradient (∼10 GV/m for SiO$_2$ [11] and ∼3 GV/m [12] for Si) inside a microstructure.

Over the past 30 years, various setups have been proposed to optimize the acceleration process [13–18]. Many fundamental functions required in an on-chip particle accelerator, such as acceleration, bunching, deflection and focusing have already been demonstrated experimentally using DLAs [19–22]. However, it is still a remaining challenge to accelerate the electrons in the non-relativistic regime with ultrashort pulses. A chirped grating acceleration structure was proposed to enhance the interaction length [23], where a phase shift is introduced onto the electric field, allowing the electron to avoid the deceleration cycle [13]. However, the acceleration process is still limited by the pulse duration $\tau$. For uncorrelated, laterally impinging pulses, a 100 fs pulse, for example, would result in $v_0\tau = 6 \mu$m with initial velocity $v_0 = 0.2c$. A pulse with a longer duration may be used to enlarge the interaction length, but this requires larger input energy at given electric field strength. The damage threshold fluence of the acceleration structure material prohibits such an approach or requires resort to a lower field amplitude.

A tree-network waveguide approach [24] redistributes the entire acceleration into multiple series of interactions with short laser pulses. However, it is overly complex for practical implementations. Currently among DLAs, the common approach to implement short laser pulses for a long acceleration length is by utilizing a pulse-front-tilted (PFT) laser pulse [14, 18, 25, 26]. The PFT scheme brings in a delay of the pulse along the particle acceleration direction $x$ (See Fig. 1 for coordinates definition), making the short laser pulses at a given location $x$ arrive simultaneously with the electron. However, the PFT scheme can only match the driving laser with a fixed electron velocity, which fulfills $\tan \alpha = c/v$ and $\alpha$ represents the PFT angle. As a result, a walk-off occurs between the laser pulse and sub-relativistic electrons when the velocity increases due to acceleration.

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The PFT corresponds to a linear laser pulse arrival time along $x$. However, the electron velocity changes drastically during the acceleration. To overcome the sub-relativistic acceleration difficulty, the laser pulse needs to catch up with the rapidly changing electron, i.e., a continuously changing PFT angle, resulting in a curved laser intensity front.

In this letter, we propose an all-optical spatio-temporal coupling (STC) controlled driving laser pulse, which changes its tilt angle according to the increasing velocity of the electron (see Fig. 1). It is combined with a chirped dielectric structure $[23]$. Mid-infrared laser (10 μm) which can be generally achieved via OPCPA $[27, 28]$ is used in this simulation. A longer wavelength will lead to higher breakdown threshold due to the multiphoton ionization and permit larger apertures for higher charge. The proposed scheme converts the temporal manipulation of the laser pulse into a spatially varying delay, which can be achieved by manipulating the group delay dispersion (GDD, $\Phi_2$) and third-order dispersion (TOD, $\Phi_3$). The STC scheme extends the interaction length and enhances the kinetic energy gain. Moreover, it retains high flexibility in the optical operations for creating the driving laser pulse.

II. Results

The configuration we propose is shown in Fig. 1(a). Due to a symmetric setup with counter-propagating ($x$-polarized) pulses, the magnetic fields cancel out at the channel center (P.2), and the electric fields add up. In Fig. 1(b), the sketches of three different cases of spectral phase induced PFTs are presented.

In order to analyse the STC in detail, we chose to look into two aspects. One is the perfect phase-matched situation shown in Fig. 2 where the electron with 0.1 eV initial kinetic energy, typical excess energy for photoelectron $[29]$, is used. In the perfect phase-matched situation, the driving electric field $Re[E(x, t)]$ in Eq. (4) (Methods section) is replaced by $|E(x, t)|$, where $||$ represents the absolute value. In other words, the electron is assumed to remain on the peak of the field. This corresponds to the ideal design of the acceleration structure where no dephasing between the driving field and the electron occurs. This gives us insights on the maximum kinetic energy gain with the given parameters. The other is the acceleration results of a 20 keV electron with a specific acceleration structure shown in Figs. 3 and 4. This gives realistic guidance to future experimental work. The results with different initial electron energy can be found in SM Section VI.

In Fig. 2(a), the kinetic energy gain of a slow electron (0.1 eV) with a perfect phase-matched electric field is presented as a function of the GDD and TOD. A factor of 0.7 is included to take into consideration of the evanescent field effect, which is an approximate average of the structure constants of common DLA cells in the range 0.1 eV to 0.6 MeV. The maximum kinetic energy gain is $\sim$ 0.6 MeV. It can be seen that the STC scheme is particularly advantageous for extremely low initial electron energies, i.e., large energy range. The electric field envelopes $|E(x, t)|$ are presented in 2(b,c), where the white dashed line represents the electron injection position $x = -0.45\sigma_{FWHM}$ and $\sigma_{FWHM}$ is the full-width-half-maximum of the beam size at P.2. Additionally, the electric fields at larger $t$ values ($t > 0$) arrives later than that with smaller $t$ values ($t < 0$). Note that for the convenience of the representation, in...
Fig. 2(b,c) \( x = 0, t = 0 \) is chosen to be where the peak intensity of the laser beam locates. In Figs. 3 and 4, the initial electron acceleration location with the white dashed line is denoted as \( x = 0 \). It can be seen that the GDD and TOD drastically influence the PFT shape. The TOD modifies the PFT along \( x \), leading to a continuously matching PFT for the entire electron acceleration.

For the STC scheme, the beam size and pulse duration at \( P.2 \) largely depend on the parameters of the entire system. We focus on a 2D+1 \((x, z, t)\) model where the electric fields in the frequency domain and the time domain are connected by Fourier transform \( E(x, z, t) = \mathcal{F}[E(x, z, \omega)] \). Note that we use the complex notation for the electric fields and only the positive half of the spectrum is used i.e. \( \omega > 0 \). The electric field used to calculate the electron acceleration is \( \text{Re}[E(x, z, t)] \), where "Re" represents taking the real part. The incident electric field in the frequency domain before the grating at \( P.1 \) follows the expression:

\[
E_1(x, 0, \omega) = A_1 \exp \left( -i k x^2 / q_1 \right) \exp \left( -\Delta \omega^2 \tau^2 / 4 \right) \\
\times \exp \left[ i(\Phi_2 \Delta \omega^2 / 2 + \Phi_3 \Delta \omega^3 / 6) \right],
\]

where \( A_1 \) is a constant representing the amplitude, \( q_1 = i \pi \sigma_1^2 / \lambda_0 \) is the q-parameter for a Gaussian pulse, \( \sigma_1 \) is the beam size, \( k = 2 \pi / \lambda_0 \) is the wave vector, \( \lambda_0 = 10 \ \mu m \) is the center wavelength, \( \tau_{\text{FWHM}} = 100 \ \text{fs} \) is the transform limited pulse duration (full-width-half-maximum), \( \tau = \tau_{\text{FWHM}} / \sqrt{2 \ln 2} \), \( \Delta \omega = \omega - \omega_0 \), \( \omega_0 = 2 \pi c / \lambda_0 \), \( \Phi_2 \) is the GDD, and \( \Phi_3 \) is the TOD. The electric field for electron acceleration at \( P.2 \) is constructed by two steps.

Firstly, the electric field reflects on the grating, propagates through the lens, and arrives at the acceleration structure. These are calculated analytically via the ABCDEF matrix method \([32]\) (see Supplementary material, referred to as SM, Section I). The analytical expression of the electric field right before the acceleration structure is shown as the following:

\[
E_2(x, 2f, \omega) = A_2 \exp \left[ -i k (x - \beta \Delta \omega f)^2 / q_2 \right] \exp \left( -\tau^2 \Delta \omega^2 / 4 \right) \\
\times \exp \left[ i(\Phi_2 \Delta \omega^2 / 2 + \Phi_3 \Delta \omega^3 / 6) \right],
\]

where \( \beta \) is the angular dispersion induced by grating at \( P.1 \), and \( f \) is the focal length of the lens. The choice of \( \beta \) can be found in SM Section II. The parameters \( A_2 \) and \( q_2 \) are amplitude and the q-parameter at \( P.2 \), which depend on \( \beta \) and \( f \) (see explicit expression in SM Section I). Note that Eq. (2), is the expression at the focal point i.e. the propagation distance after the lens is \( f \). In principle, the propagation distance between the lens and the acceleration structure is \( f - h \). We found that the extra propagation distance \( h \) has a minor influence on acceleration results with our parameter choices since \( f \sim cm \) and \( h \sim \mu m \). Moreover, we assume perfect lenses where the focal length for all frequencies are the same. Thus, we present the electric field at \( P.2 \) at the focal length as shown in Eq. (2). Secondly, each acceleration structure period \( \bar{w}_n \) is iteratively calculated with the electron acceleration process \([23, 33]\). In other words, upon entering the acceleration structure, the electron velocity \( v_0 \) is used to calculate the first acceleration structure period, \( w_1 = \lambda_0 v_0 / c \). The accelerator structure introduces a \( x \)-dependent delay onto the driving field as shown in Fig. 3(a). Without the loss of generality, a smooth flat-top function is used as an approximation of the
FIG. 3. Acceleration of a 20 keV electron with a specific acceleration structure. (a) shows the delay of the laser pulse induced by the first period of the acceleration structure. (b) shows the phase \((\tan^{-1}\{\mathrm{Im}[E(x,t)]/\mathrm{Re}[E(x,t)]\} - \omega_0 t\) along the electron trajectories in (c) and (d) (black curves) where the electric field distribution for STC and PFT is shown as function of \(x\) and \(t\). Note that the electric field presented is for location \(P.2\) with a fixed \(z\). It can be seen that for the STC scheme, the electric field carries a curved phase-front, whereas the PFT scheme has a flat phase-front.

The phase of the electric field that the electron experiences, i.e., \(\Delta E\) of the pulse at the vacuum and tooth/pillar regime within one period of the acceleration structure is taken and the pillar section take is \(1\) keV, the first period of the acceleration structure with the parameters shown in Fig. 3(a). In our work, the maximum phase difference of the pulse at the vacuum and tooth/pillar regime within one period of the acceleration structure is taken as \(\pi\). With the parameters of Figs. 3 and 4, acceleration results of the optimal design i.e. the perfect phase-matched STC scheme with the same parameters is shown by the blue dashed curve as a reference. The perfect phase-matched STC scheme with the same parameters is shown by the blue dashed curve as a reference. The optical lasers at \(P.2\) of the three schemes are chosen to have the same beam size and pulse duration. The kinetic energy gains are presented in Fig. 4(a). The perfect phase-matched STC scheme with the same parameters is shown by the blue dashed curve. The perfect phase-matched STC scheme has an adapting one. The instantaneous PFT angle is derived from the electric field velocity (solid blue line in (a)). The electric field carries a curved phase-front, whereas the PFT scheme has a flat phase-front.

shape of the delay. With the acceleration structure material as silicon \((n_{\text{Si}} = 3.5)\) and initial kinetic energy 20 keV, the first period of the acceleration structure \(w_1 = 2.7 \mu\text{m}\). For each period of the acceleration, both vacuum and the pillar section take 50% length of the entire period as shown in Fig. 3(a). In our work, the maximum phase difference of the pulse at the vacuum and tooth/pillar regime within one period of the acceleration structure is taken as \(\pi\). With the parameters of Figs. 3 and 4, acceleration results of the optimal design i.e. the perfect phase-matched pulse are presented in Fig. S6 in the SM section IV. The specific design is beyond the focus of this work and can be found in the work of Niedermayer et. al [17, 26]. The phase of the electric field that the electron experiences, i.e. phase deviation the structure needs to be designed to correct, is shown in Fig. 3(b).

After traveling through distance \(w_1\), the new electron velocity is used to calculate the next acceleration structure period \(w_2\), and this process repeats till the end of the acceleration. The evanescent field effect of each period is calculated by \(\exp[-0.5(\sqrt{2\pi/w_0})^2 - k^2]\), where \(l = 1 \mu\text{m}\) is the gap distance between the two facing acceleration structures. The evanescent field decay factor varies from \(\sim 0.3\) to \(\sim 0.7\) in Fig. 3(c). The PFT used for comparison in Fig. 3(b,d) is defined in [14, 25]. In Fig. 3(c,d), the electric field along the acceleration direction \(x\) versus the time \(t\) at \(P.2\) (a fixed \(z\)) is plotted. It can be seen that the STC has a curved phase-front whereas the PFT scheme has a flat phase-front. More comparisons between the PFT and STC schemes are presented in SM section III. Due to the continuously changing intensity front, the electron stays within the pulse in the STC scheme for the entire acceleration process. In contrast, for the PFT scheme, the electron walks off immediately with the pulse.

Figure 4 presents the comparisons among the STC scheme, PFT scheme, and the no-tilt (direct transverse injection without any pulse-front-tilt) scheme, where the acceleration results of the STC and PFT schemes are outcomes of the electric fields presented in Fig. 3(c,d) respectively. The optical lasers at \(P.2\) of the three schemes are chosen to have the same beam size and pulse duration. The kinetic energy gains are presented in Fig. 4(a).

FIG. 4. Comparisons among the STC, PFT and no-tilt schemes for the electron with 20 keV initial kinetic energy. (a) shows the kinetic energy gain \(\Delta E\) with peak field strength \(E_0 = 2 \times 2.25 \text{ GV/m}\). The perfect phase-matched STC scheme with the same parameters is shown by the blue dashed curve. The perfect phase-matched STC scheme with the same parameters is shown by the blue dashed curve as a reference. (b) shows instantaneous electric field experienced by the electron. (c) shows a comparison of the tilt angle along the acceleration direction \(x\), where the PFT scheme has a constant tilt angle, while the STC has an adapting one. The instantaneous PFT angle is derived from the electric field distribution for STC and PFT is shown as function of \(x\) and \(t\). It can be seen that for the STC scheme, the electric field carries a curved phase-front, whereas the PFT scheme has a flat phase-front.

The phase of the electric field that the electron experiences, i.e., \(\Delta E\) of the pulse at the vacuum and tooth/pillar regime within one period of the acceleration structure is taken as \(\pi\). With the parameters of Figs. 3 and 4, acceleration results of the optimal design i.e. the perfect phase-matched STC scheme with the same parameters is shown by the blue dashed curve as a reference. The perfect phase-matched STC scheme with the same parameters is shown by the blue dashed curve as a reference. The optical lasers at \(P.2\) of the three schemes are chosen to have the same beam size and pulse duration. The kinetic energy gains are presented in Fig. 4(a). The perfect phase-matched STC scheme with the same parameters is shown by the blue dashed curve. The perfect phase-matched STC scheme has an adapting one. The instantaneous PFT angle is derived from the electric field velocity (solid blue line in (a)). The electric field carries a curved phase-front, whereas the PFT scheme has a flat phase-front.
case for all three cases can be found in Fig. S6 in SM section IV. The peak electric field strength illuminating on the acceleration structure before considering the evanescent field effects is 2.25 GV/m from each side. Figure 4(a) indicates that a matching PFT enhances the acceleration energy drastically. The STC scheme should show greater advantages with higher acceleration field strength. The instantaneous electric fields the electron experiences along the acceleration position \( x \) are shown in Fig. 4(b). It can be seen that for the PFT and no-tilt schemes, the electron walks off with the pulse imminently whereas, for the STC scheme, the electron sees the acceleration field for a longer interaction length. In Fig. 4(c) the PFT angles are presented. The black curve is presented as a reference, where the instantaneous PFT angle is calculated from the electron velocity i.e. \( \text{tan}(\text{angle}) = c/v(x) \). The PFT angle of the PFT scheme is a constant \( c/v_0 \). Note that the acceleration structure extends over the entire \( x \), the relatively moderate electron energy increment after \( x > 0.15 \text{mm} \) is due to the decreasing electric field strength.

In all the calculations presented in this letter, we assume a constant distribution along \( y \) dimension with the beam size \( \sigma_y = 0.2 \text{ mm} \) and calculate the total input energy as \( 0.48 \text{ mJ} = 0.5 \varepsilon \varepsilon_0 \sigma_y \int |E(x, 0, \omega)|^2 dx d\omega = 0.5 \varepsilon \varepsilon_0 \sigma_y \int |E(x, 2f, \omega)|^2 dx d\omega \), where the \( \varepsilon_0 \) is the vacuum permittivity.

### III. Discussion

We present an all-optical-controlled scheme for non-relativistic electron acceleration in the DLA via the spatio-temporal coupling controlled driving pulse. It is promising especially for the acceleration of non-relativistic electrons with high electric field strength, where the electron velocity varies drastically during the acceleration process. The STC shows the possibility of high precision PFT angle control by converting the temporal variation into a spatial manipulation, which highly relaxes the nano-scale fabrication precision and increases the feasibility of implementing such a scheme with dielectric structures.

Owing to the continuously matching PFT, STC provides long interaction length and high kinetic energy gain. The optical configuration enables unique continuous tunability of the optical intensity front shape by changing the GDD and TOD. The scheme is a general method that could potentially be applied to driving fields of other wavelengths. Our results bring new possibilities to portable electronic devices and table-top acceleration experiments.

The STC scheme enables high flexibility of the optical system elements. There is no constrain of the focal length, as long as the electron interaction point and the grating are positioned at each side of the lens’ focal points. Additionally, this scheme enables high tunability since the PFT is defined by \( \Phi_2 \) and \( \Phi_3 \), which can be controlled by a commercially available acoustic-optical modulator. It offers independent programmable adjustment of GDD, TOD and higher-order dispersion on-the-fly. Meanwhile, the adjustment of GDD and TOD does not influence the pre-aligned optical system. It provides the possibility of fine adjustment of even higher order dispersion through electron feedback. Machine leaning [35, 36] can also be implemented into the system to optimize the beam properties. Most importantly, the TOD modifies PFT along the \( x \) dimension, resulting in a curved PFT that enables a continuously matching driving field to the electron beam for the entire acceleration process, which is crucial for high energy acceleration with short acceleration lengths. This largely enhances the flexibility of the experimental implementations.

### IV. Methods

This proof-of-concept demonstration is based on a single electron model. Detailed demonstrations of electron beam dynamic can be found in [26, 34]. The Leap-Frog method is used to numerically calculate the relativistic electron position and velocity as the following

\[
\frac{\partial x}{\partial t} = v \\
\frac{\partial p}{\partial t} = -eRe[E(x, t)],
\]

where \( e > 0 \) is the elementary charge, \( p = mv/\sqrt{(1 - v^2/c^2)} \) is the electron momentum. The electric field \( E(x, t) \) is the resulting field from \( E_0(x, t) \) after adding the periodic delay caused by the acceleration structure/spatial grating (see Fig. 5(c,d)). Note that the position of the incident electron is at the exact gap center of the acceleration structure, where no net magnetic field or deflecting field exists. The electron injection location is at \( x = -0.45 \sigma_{FWHM} \) in Fig. 2(b,c) marked by the white dashed line. The injection time is synchronized at the peak of the temporal envelope at \( x = -0.45 \sigma_{FWHM} \). The initial injection electric field phase is chosen such that the final kinetic energy
gain is the maximum. Our method takes < 60 s for a single CPU on a standard PC (Intel(R) Core (TM) i5-10400 CPU @ 2.9 GHz). The convergence test can be found in SM section V.

Data availability statements:
The code/data developed for this work is publicly available upon request to the corresponding authors.

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Author contributions:
L.W and D. F. Zhang conceived and coordinated the project. L.W developed the numerical and mathematical model. U.N made substantial modifications to the work and the manuscript. All authors contributed with helpful discussions of the work.

Conflict of Interest:
The authors declare no conflicts of interest.

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