THz-DRIVEN DEFLECTION OF ULTRASHORT ELECTRON BUNCHES

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Abstract

Accurate characterization of the longitudinal properties of ultrashort electron bunches is essential for advancing scientific applications of compact particle accelerators. Here, we propose an on-chip integrated terahertz (THz)-driven dielectric particle deflector based on the inverse Cherenkov effect. By illuminating two symmetric right-angle prisms with linearly polarized THz pulses at a 180° phase difference, synchronized evanescent waves are excited on the prism hypotenuse surfaces, where phase matching between the particle velocity and the surface wave velocity generates a sustained transverse deflection force. This scheme overcomes the intrinsic limitations of conventional radio-frequency deflectors in both achievable frequency and cavity breakdown threshold. Particle-in-cell simulations with a 1 MeV, 110 fs electron bunch demonstrate a femtosecond-level temporal resolution of ~36 fs under a deflection gradient of 0.112 MV/m. Furthermore, scalability analysis indicates that the resolution can be extended to the sub-femtosecond regime by increasing the interaction length or employing higher-intensity THz sources. The proposed deflector provides a compact and scalable platform for on-chip longitudinal bunch diagnostics, with promising applications in ultrafast electron diffraction and attosecond science.

INTRODUCTION

Transverse deflection structures (TDS) have been widely used as diagnostics and optimization devices to characterize longitudinal properties of electron bunches in many electron bunch-based scientific facilities such as ultrafast electron diffraction (UED) and microscopy (UEM), free electron laser (FEL), dielectric laser accelerator (DLA), laser-driven (LWFA) and bunch-driven plasma wakefield accelerator (PWFA) [1, 2]. The X-band (11.4 GHz) TDS with compact design have demonstrated its ability to achieve femtosecond and sub-femtosecond longitudinal resolution, the recent experiments even show that sub-femtosecond resolution can be achieved at the C-band (5.7 GHz) range [3–5]. However, emerging applications like femtosecond and attosecond pulses demand bunch diagnostics shorter than femtoseconds, a regime where conventional RF deflectors face two intrinsic limitations: (i) the low breakdown threshold of metallic cavities, and (ii) the lack of high-power sources at frequencies beyond the X-band [6].

In this work, we propose a THz-driven dielectric particle deflector that allows one to record the complete longitudinal information of an ultrashort electron bunch which can be integrated on chip. Through accurate control of two incident THz laser pulses' phase shift to 180°, the bunch channel constructed by symmetric dual prisms can generate a continuous synchronized deflecting force. In a two-dimensional model, the fields can be decomposed into TE (with E_y, H_x, and H_z nonzero) and TM (with E_x, E_z, and H_y nonzero) polarization. The deflecting strength can be adjusted via THz field intensity, enabling deflecting gradients from MV/m to GV/m over micron-to-millimeter scales. Here, a simulation is presented to demonstrate the deflecting capability of dielectric prisms structure with a MV/m scale via inverse Cherenkov effect. Such a THz-driven dielectric particle deflector should have wide applications in many electron bunch-based facilities.

STRUCTURE DESIGN

The schematic diagram of the proposed THz-driven electron bunch deflecting scheme is shown in Fig. 1. The design leverages the unique advantages of the THz regime, which bridges radio frequency and optical domains, to achieve both extended linear interaction lengths and higher than femtosecond-level temporal resolution. The perpendicularly incident single-cycle parallel-polarized THz pulses, generated via narrow band emission or optical rectification in lithium niobate (LN) crystals or other nonlinear organic materials, are used as driven laser pulses in prism micro structures. The electron bunch traverses a gap between prisms, interacting with evanescent waves generated via total internal reflection at the prism hypotenuse surfaces. The phase difference between the two incident THz pulses is set to 180°, which causes the longitudinal acceleration electric fields (E_z) along the axis to cancel each other out, while the transverse deflection electric fields (E_x) are superimposed. Phase-matching between the electron velocity β_b and surface wave phase velocity β_p is achieved by optimizing the prism refractive index n and THz incidence angle θ, satisfying $\beta_b = \beta_p = (n \sin\theta)^{-1}$. Here, the longitudinal center of the electron bunch remains aligned with the zero phase position of the surface wave, which can achieve the maximum deflecting gradient.

In order to fully understand the interaction between particles and deflection fields, we first define the input optical source. The incident THz pulses are modeled as single-cycle Gaussian waveform:

$$E(t) = E_0 \exp(-0.5((t - t_0)/\sigma)^2) \sin[\omega_0(t - t_0)]. \quad (1)$$

where E_0 is the peak field, σ is the rms pulse duration, t_0 the time delay, and ω_0 the central angular frequency. Figure 2(a) shows the temporal profile of the THz pulse, with a pulse duration of 0.45 ps, while Fig. 2b shows its frequency spectrum centered at 1 THz (bandwidth: 0.98 THz).

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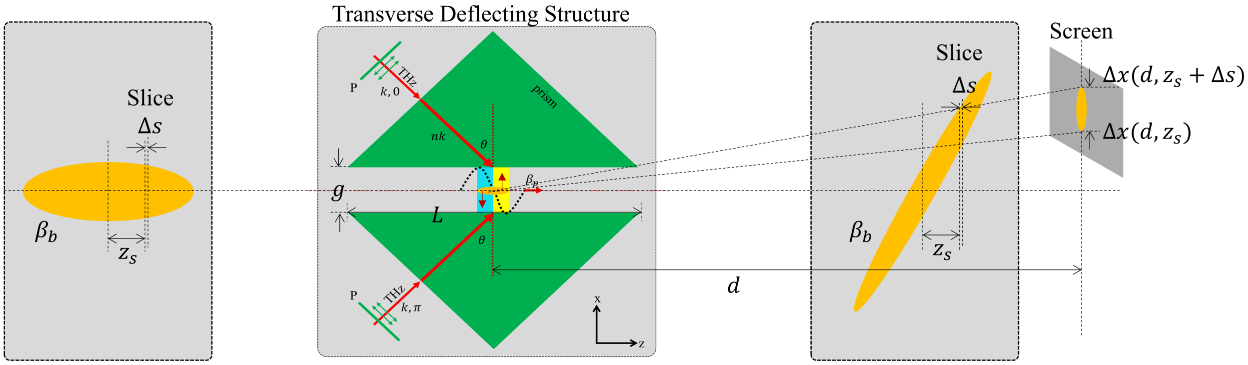

Figure 1: Schematic diagram of the proposed THz-driven electron bunch deflecting scheme. Key components include: (i) lithium niobate (LN) crystals for THz generation; (ii) symmetric silicon prisms with a 300 µm bunch channel (iii) 180° phase-shifted, parallel-polarized (P) THz pulses. Here, k and nk denote the vacuum and dielectric wavenumbers, respectively.

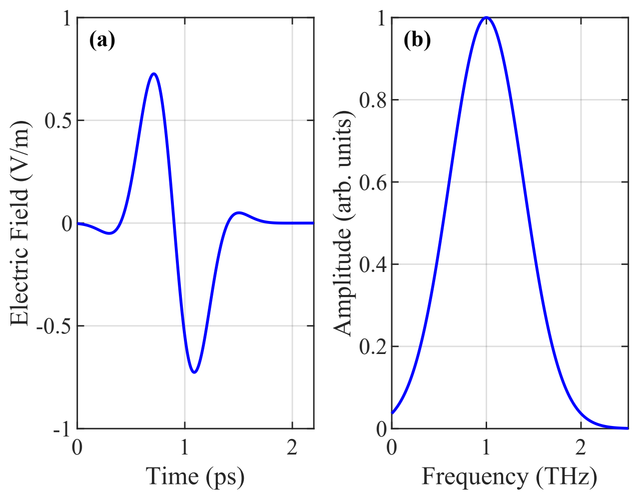

Figure 2: (a) THz pulse in the time domain and (b) Frequency spectrum used in simulations.

The electron bunch with Gaussian distributions in both transverse and longitudinal directions is employed as the particle source. The electron bunch is characterized by an initial energy of E_k, a charge of Q, a longitudinal length of σ_z, a transverse size of σ_x, and a normalized emittance of ϵ_n. The parameters of the THz pulses used in simulations, together with the particle source, are given in Table 1.

Table 1: Driven optical source and particle source simulation parameters.

Physical Quantity	Symbol	Value
central frequency	f_0	1 THz
pulse duration	σ_t	0.45 ps
bunch energy	E_k	1 MeV
bunch charge	Q	1.6 fC
bunch length	σ_z	110 fs
bunch size	σ_x	10 µm
normalized emittance	ϵ_n	1 pm·rad

SIMULATION AND RESULTS

The distribution of deflection field in the channel is calculated by FDTD algorithm. In the simulation, the transverse distribution of the THz pulse is set to be uniform, ensuring the uniformity of the field distribution at different times during the propagation of the surface wave formed by total reflection.

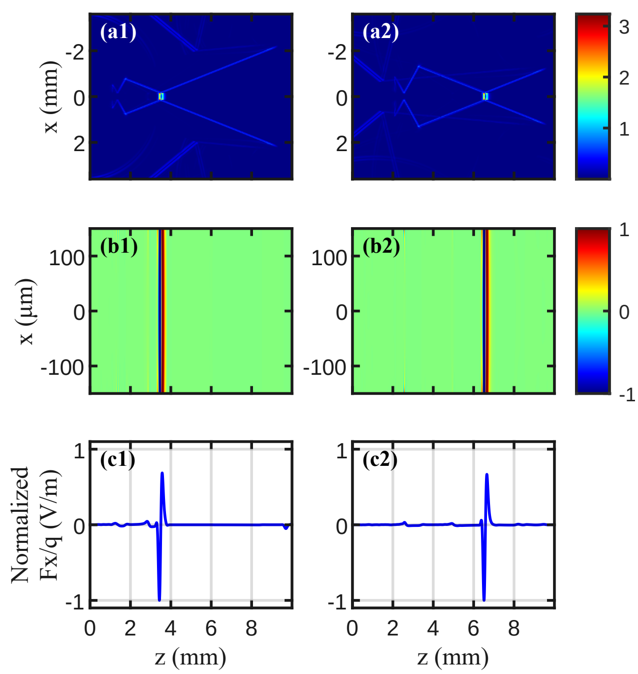

Figure 3: (a) Simulated snapshots of the laser pulse propagating in the channel at two moments. (b) Field maps of the E_x field in the bunch channels at two moments. (c) Distribution of F_x/q fields along the z-axis at two moments.

Figure 3 captures the THz pulse evolution at t_1= 8.78 ps and t_2= 19.70 ps. The electric field magnitude (Fig. 3a) exhibits confinement within the prism structure, while the transverse field E_x distributions (Fig. 3b) and deflection force F_x/q distributions along the z-axis (Fig. 3c) in the bunch channel demonstrate symmetric profiles, consistent with the 180° phase-shift design. From Fig. 3b, the deflect-

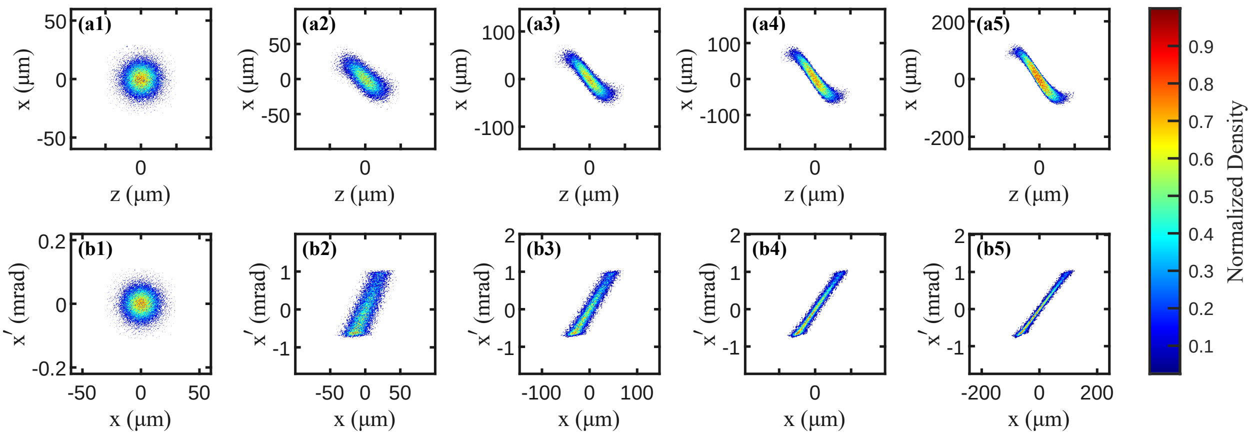

Figure 4: Simulated electron bunch evolution at five moments (t_1 = 0, t_2 = 8.86 ps, t_3 = 17.72 ps, t_4 = 26.58 ps, t_5 = 35.44 ps) along the electron bunch channel. (a) The real space distributions in z-x plane . (b) The phase space distributions in x-x' plane.

ing force is symmetrically distributed on both sides of the z-axis, consistent with the theoretical analysis. From Fig. 3c, the THz pulse maintains >90% of its initial amplitude over the 8 mm interaction length (Fig. 3c), with negligible dispersion induced broadening (<5% pulse width increase), ensuring sustained deflection efficiency. Phase velocity extraction from Fig. 3c yields β_p = 0.941, matching the 1 MeV bunch velocity β_b = 0.941 within 0.1% error.

Figure 4 tracks the bunch's phase space evolution at five time slices. The longitudinal profile of the electron bunch is observed to exhibit negligible variation. Meanwhile, a progressive amplification of both the transverse distribution and the transverse component of momentum is noted. Initial simulation transverse size (σ_{x1} = 9.862 μm) expands to 48.805 μm after 35.44 ps of deflection, corresponding to a deflection gradient of 0.112 MV/m. This value agrees well with the expected gradient of ~ 0.12 MV/m, obtained from the 1 MV/m incident E_x field after the $1/\beta\gamma^2$ cancellation of the electric and magnetic Lorentz terms for the 1 MeV bunch. The longitudinal spread remains below 2% (σ_{z5} = 110.404 fs). The linear relationship between transverse displacement and longitudinal position is confirmed (with R^2 = 0.97 as shown in Fig. 4), indicating that the mapping from temporal profile (σ_{z1} = 108.549 fs) to spatial distribution (σ_{x5} = 48.805 μm) is direct. When the TDS is off, the bunch transverse size and longitudinal length is $\sigma_{x,off}$ = 15.149 μm and $\sigma_{z,off}$ = 110.152 fs, respectively. Under this condition, the temporal resolution of the THz-driven dielectric deflector can be estimated to ~36 fs by Eq. 2.

$$R_t = \frac{\sigma_{x,off} \cdot \sigma_z}{\sqrt{\sigma_{x,on}^2 - \sigma_{x,off}^2}} \tag{2}$$

This formula is analogous to that of the classical RF TDS.

CONCLUSION

In conclusion, we propose a particle deflecting scheme using a pair of single-cycle THz pulses to drive dielectric prisms via the inverse Cherenkov effect. The electron bunch deflecting is obtained via maintaining synchrony between the center of the electron bunch and the zero-phase point of the surface wave. The bunch size that can be effectively deflected is directly proportional to the linear region of the surface wave, which is in turn proportional to the wavelength of the incident laser. The deflecting gradient is related to the initial energy of the electron bunch and the intensity of the incident laser. This THz-driven dielectric particle deflector is significant not only for femtosecond-level bunch diagnostics, with applications extendable to ultrafast electron diffraction and attosecond science.

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