

Multidimensional phase-space manipulation for attosecond electron bunch compression

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Attosecond electron beams are essential for investigating ultrafast structural and electronic dynamics in matter with atomic-scale resolution. We propose a novel method that enables robust attosecond-level electron bunch compression. This method employs THz-driven linear energy chirping and multidimensional phase-space manipulation, effectively compressing the electron bunch and suppressing its arrival timing jitter. Implemented in an MeV ultrafast electron diffraction beamline, this method compresses a 3.18 MeV electron beam from an initial duration of 747 fs (rms) to 810 as (rms) while retaining 6 fC of charge, with 886 as (rms) arrival-time jitter. This approach enables unprecedented timing resolution in ultrafast sciences and offers significant potential for other accelerator applications involving attosecond-scale electron beams.

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I. INTRODUCTION

Electron beam-based ultrafast techniques, particularly ultrafast electron diffraction (UED), have become a vital tool for investigating atomic-scale structural dynamics with femtosecond temporal and ångström spatial resolution [1–5]. While conventional UED resolves nuclear motion on femtosecond scales, this emerging frontier aims to directly probe even faster phenomena, such as electronic dynamics and laser-field interactions, which evolve on attosecond timescales and place new, demanding requirements on electron beam sources [6,7]. The temporal resolution of UED is fundamentally constrained by the duration and shot-to-shot arrival-time jitter of the electron bunch [8]. Early implementations of UED relied on photocathode-driven electron guns operating at tens to hundreds of kiloelectronvolts [8–10]. These nonrelativistic beams experienced severe pulse broadening due to space-charge force and temporal dispersion during dc acceleration, imposing a hard limit on achievable time resolution [9,11].

In recent years, extensive efforts have been devoted to pushing the temporal boundary of UED. Photocathode radiofrequency (rf) guns at MeV energies took advantage of relativistic mitigation of space-charge forces, enabling

generation of much shorter pulses [2,12]. Conventional rf compression approaches that imprint an energy chirp via cavity phase modulation and use velocity bunching in drift sections can produce sub-20 fs pulses but introduce tens of femtoseconds of arrival-time jitter due to rf phase noise [13,14]. Laser-driven THz bunchers eliminate phase jitter through intrinsic laser-THz synchronization, yet residual rf amplitude instabilities and downstream beamline dispersion convert energy fluctuations into 70 fs of timing jitter [15,16].

The use of double-bend achromat compressors addresses rf amplitude sensitivity by engineering isochronous transport, remarkably reducing timing jitter to a few femtoseconds [17]. Despite these advances, state-of-the-art compression methods still cannot reach the attosecond regime, because higher-order nonlinearities in the longitudinal phase space induce pulse broadening, and aggressive collimation to suppress space-charge tails drastically reduces usable beam charge. These challenges underscore that two-dimensional manipulation in the longitudinal phase space can hardly simultaneously achieve subfemtosecond durations, suppress timing jitter, and preserve high bunch charge, highlighting the urgent need for a new compression paradigm.

In this work, we introduce a multidimensional phase-space manipulation strategy that realizes attosecond-level compression of MeV electron beams while preserving beam quality. By combining pulse-front-tilt laser-induced transverse-to-longitudinal coupling at the photocathode, THz-driven linear energy chirping immune to rf jitter, and a specially designed beamline that converts transverse

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emittance into longitudinal compression, this method simultaneously compresses the electron bunch to attosecond durations, decouples arrival-time fluctuations from rf amplitude noise, and preserves bunch charge.

II. MULTIDIMENSIONAL PHASE-SPACE MANIPULATION

The schematic layout of the proposed method is illustrated in Fig. 1. An 800 nm laser is split into three branches. The first branch undergoes third-harmonic generation to produce a 266 nm ultraviolet pulse, which illuminates the photocathode to generate the photoelectron beam. The second branch is employed to generate a THz pulse via optical rectification [18], while the third serves as the pump laser. To achieve the required transverse-to-longitudinal emittance partitioning, we implement the angular dispersion-induced microbunching (ADM) scheme [19]. This configuration consists of three stages: a magnetic dipole first introduces angular dispersion to the electron beam; a modulator then imposes a controlled energy chirp; and finally, a dogleg with combined transverse and longitudinal dispersion compresses the electron beam. Originally developed for generating periodic microbunches in electron beams through precise control of transverse-longitudinal phase-space correlations, the ADM approach enables the final duration of each microbunch to be determined by the initial angular divergence, allowing for much shorter temporal durations than those achievable through energy modulation alone.

As the electron beam traverses the first dipole magnet of the ADM line, intrinsic transverse-longitudinal coupling leads to temporal elongation of the bunch by several tens of femtoseconds. While negligible for longer pulses, this elongation introduces nonlinear distortions in the THz-driven energy modulation stage when dealing with ultra-short femtosecond beams, degrading compression quality. To suppress these distortions, we employ a pulse-front-tilted laser to illuminate the photocathode, as depicted in Fig. 1. The pulse-front tilt (PFT) imprints a time-position correlation directly at the emission point, precompensating the dipole-induced coupling. This tilt can be realized either by injecting the laser at an oblique angle or by spatially dispersing it using a prism or diffraction grating.

III. THEORETICAL FORMULATION

This pulse-front tilt creates a one-to-one mapping between the longitudinal positions of the electrons and their transverse coordinates, as shown in the upper panels of Fig. 1(a). After acceleration in the rf gun and propagation through a drift section characterized by longitudinal dispersions R_{56}^{gun} and R_{56}^{drift1} , the electron beam enters the ADM section. Upon exiting the first dipole with bending angle b , the initial x - z correlation introduced by the tilted laser is effectively canceled [Fig. 1(b), upper panels], thus suppressing nonlinear distortions in the following THz modulation. In the longitudinal phase-space view [Fig. 1(a), lower panels], the beam initially acquires a positive energy chirp (the head carries higher energy than the tail) due to space-charge forces in the gun. As the bunch drifts with

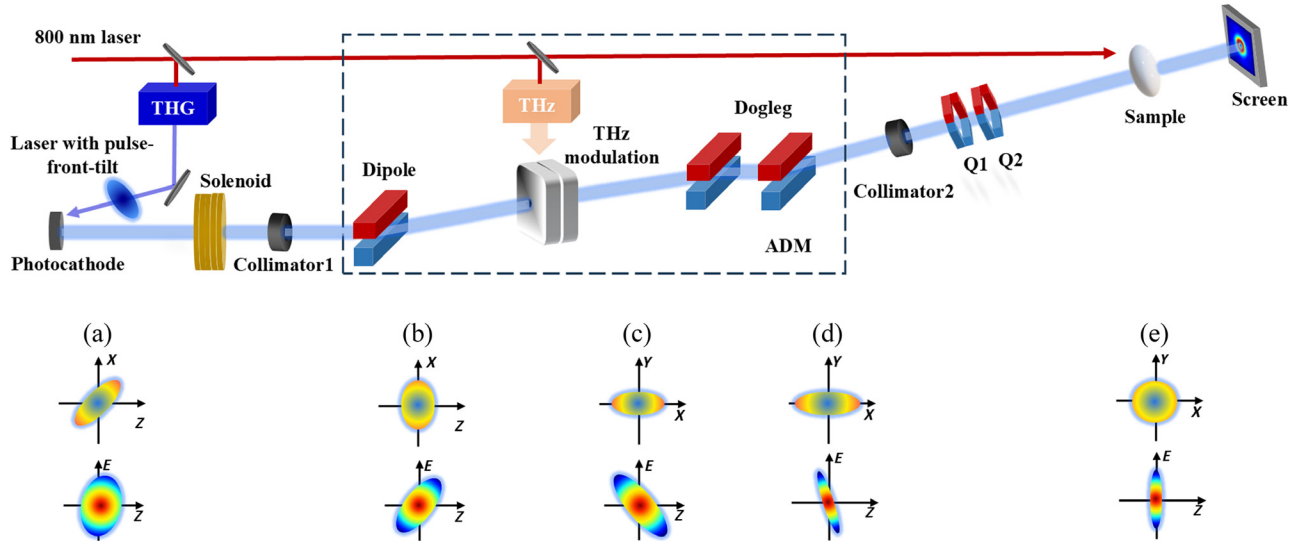


FIG. 1. Schematic of the multidimensional phase-space manipulation beamline. A pulse-front-tilt UV laser illuminates the photocathode to generate the electron beam. The beam is then accelerated in the rf gun, with its transverse size controlled by a solenoid lens, before entering the ADM beamline, where transverse divergence is converted into longitudinal density compression. Skewed quadrupole doublets (Q1, Q2) subsequently restore symmetric transverse emittances. The multidimensional phase-space evolution of the electron beam from the cathode to the sample is illustrated in (a)–(e). The color shading is used for qualitative visual guidance only and does not represent a quantitative particle-density scale.

negative longitudinal dispersion, the faster head moves ahead, lengthening the bunch [Fig. 1(b), lower panels]. The THz modulator then overcompensates this chirp, reversing it to a negative value $h = \Delta\gamma/\gamma_0 \cdot k_s$, where k_s is the THz modulation wave number [Fig. 1(c), lower panels]. The subsequent dogleg with longitudinal dispersion R_{56}^{dogleg} and transverse dispersion η compresses the bunch [Figs. 1(d) and 1(e), lower panels]. Following this, the electron beam passes through another drift section with longitudinal dispersion R_{56}^{drift2} before reaching the sample. By appropriately tuning the dispersive properties of the first dipole, the dogleg, and the final drift, the influence of the initial energy spread on the final bunch duration can be completely eliminated, enabling the formation of an ultrashort electron bunch. In the transverse plane, the combined dispersions of the dipole and dogleg result in an asymmetric beam profile downstream of the ADM section due to emittance anisotropy [Fig. 1(d), upper panels]. To restore a symmetric transverse distribution, a skewed quadrupole doublet is introduced downstream of the ADM beamline, redistributing transverse phase space and transforming the flat beam into a round one, as illustrated in Fig. 1(e) (upper panels) [20].

The total longitudinal dispersion R_{56}^{total} accumulated from the cathode to the sample should be carefully engineered to satisfy the isochronicity condition

$$R_{56}^{\text{total}} = R_{56}^{\text{gun}} + R_{56}^{\text{drift1}} + R_{56}^{\text{ADM}} + R_{56}^{\text{drift2}} = 0, \quad (1)$$

where R_{56}^{ADM} represents the longitudinal dispersion of the ADM section. Satisfying this condition ensures that arrival-time jitter remains decoupled from rf amplitude fluctuations throughout the beamline. Under these circumstances, the final longitudinal coordinate of an electron can be expressed as

$$z_{\text{final}} = [\eta + (1 + hR_{56}^{\text{ADM}'})L^{\text{drift1}}]x' + (1 + hR_{56}^{\text{ADM}'})z + [(R_{56}^{\text{gun}} + R_{56}^{\text{drift1}})(1 + hR_{56}^{\text{ADM}'}) + (R_{56}^{\text{ADM}'} - \eta b)]\delta, \quad (2)$$

where x and x' represent the horizontal position and the divergence, respectively, z is the initial longitudinal position, $\delta = \Delta\gamma/\gamma_0$ denotes the relative energy deviation, and $R_{56}^{\text{ADM}'} = R_{56}^{\text{dogleg}} + R_{56}^{\text{drift2}}$ is the combined longitudinal dispersion of the dogleg and the second drift. Under the optimized condition of ADM [19], where $R_{56}^{\text{ADM}'} = \eta b = -(1/h)$, Eq. (2) is simplified as

$$z_{\text{final}} = \eta x', \quad (3)$$

which indicates that the final bunch duration and timing jitter are determined primarily by the angular divergence of the electron beam. In practice, the isochronicity condition and the ADM matching condition should be understood as

the optimal operating point rather than singular conditions with zero tolerance. If the system operates slightly away from this point, the dominant transverse-angular compression mapping is still preserved, while the previously suppressed z - and δ -dependent contributions are gradually reintroduced. As a result, the compression performance degrades smoothly rather than catastrophically, indicating a certain degree of experimental robustness against realistic small deviations from the ideal matching condition. By optimizing the transverse properties of the electron beam and using a collimator upstream of the ADM section, this divergence can be made sufficiently small and stable, enabling stable achievement of subfemtosecond timing performance.

IV. SIMULATION RESULTS

To demonstrate the performance of the proposed method, three-dimensional particle tracking simulations with general particle tracer [21] have been performed based on the design criteria defined in Eqs. (1) and (3). The simulation parameters are summarized in Table I. A UV laser pulse, initially 120 fs (FWHM) in duration, was stretched to approximately 1.75 ps (corresponding to a pulse-front-tilt angle of 18°) and used to illuminate the photocathode. This tilt establishes the engineered correlation between the longitudinal position z and transverse coordinate x of the emitted electrons, as shown in Fig. 2(a). At the gun exit, the electron beam has a kinetic energy of 3.18 MeV, an rms bunch length of 747 fs (rms), a charge of 0.1 pC, and an rms normalized emittance of 10 nm rad [22].

The electron beam is accelerated in a 2.33-cell S-band rf gun operating at 2856 MHz with a peak accelerating

TABLE I. Simulation parameters.

Parameter	Value	Unit
<i>Beam parameters at the gun exit</i>		
Kinetic energy	3.18	MeV
Charge	0.1	pC
Normalized emittance (rms)	10	nm rad
Project energy spread (rms)	0.5	%
<i>ADM parameters</i>		
First drift length	2	m
Second drift length	0.3	m
Solenoid magnetic field	0.0293	T
B-dipole bending angle	0.26	rad
B-dipole radius	10	cm
Dogleg bending angle	0.2	rad
Dogleg radius	5.46	cm
Drift length	5	cm
THz modulation depth	0.12	%
THz wavelength	1000	μm
Quadrupole gradient	2.92	T/m
Quadrupole length	0.04	m

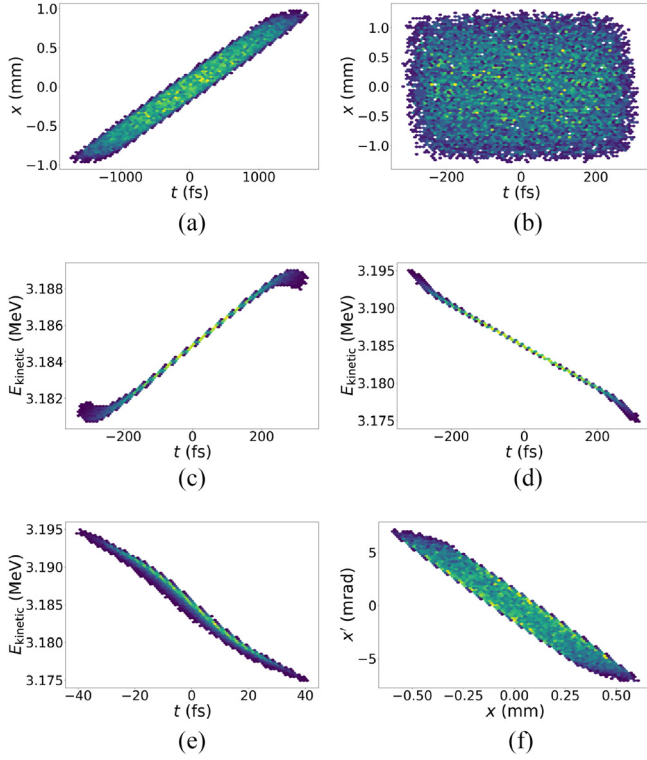


FIG. 2. Multidimensional phase-space manipulation in the beamline: (a) initial z - x phase-space correlation established via pulse-front-tilt laser illumination at the photocathode; (b) z - x phase-space postdipole bending; (c) z - δ correlation postdipole bending; (d) THz-driven chirp polarity reversal ($\delta \propto -z$) through energy modulation; (e) longitudinal density modulation after the dogleg; (f) transverse phase-space post-dogleg.

gradient of 49 MV/m at 65° . Unlike conventional 1.6-cell rf guns, this extended cavity design enables unique longitudinal beam dynamics control. A key feature of this design is the engineered alignment of the rf phases corresponding to maximum momentum gain and minimal time of flight (TOF). This alignment is verified with simulation results in Fig. 3, which plots the measured dependence of these two quantities on the gun launch phase.

The near coincidence demonstrated in the figure is the critical optimization that substantially suppresses the impact of rf phase jitter on both the bunch momentum and TOF from the cathode to the gun exit. Within the gun, the TOF depends primarily on the rf amplitude, which directly correlates with the bunch momentum, enabling the definition of a characteristic gun dispersion R_{56}^{gun} [22]. By exploiting space-charge-driven expansion during initial propagation, the gun imparts a deterministic linear energy chirp while maintaining centroid energy stability. The extended geometry not only minimizes nonlinear effects but also enables precise control and analytical characterization of the R_{56}^{gun} , yielding a well-defined and stable dispersion value. In contrast, traditional rf guns with shorter cavities are dominated by higher-order terms and lack the

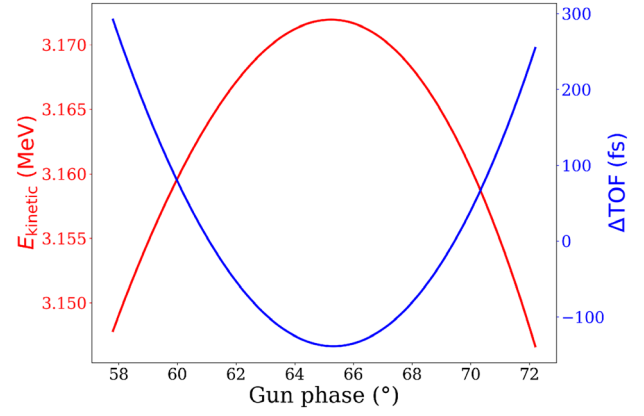


FIG. 3. Simulated bunch TOF (blue) and electron momentum (red) as a function of gun phase in the optimized 2.33-cell rf gun, showing that the phase of minimum TOF nearly coincides with that of maximum momentum.

capacity to maintain a consistent R_{56}^{gun} . The ability to isolate and tailor R_{56}^{gun} in the 2.33-cell design provides a critical degree of freedom for satisfying the isochronicity condition $R_{56}^{\text{total}} = 0$ [Eq. (1)], thus ensuring robust temporal compression that is inherently immune to rf amplitude fluctuations.

The accelerated beam then enters the first bending dipole of ADM, which introduces transverse angular dispersion. In conventional systems, this dipole would couple transverse divergence (x') into longitudinal displacement (z), stretching the bunch and introducing nonlinear phase-space distortions. This occurs because electrons with different energies follow distinct trajectories through the dipole, translating the energy spread into deviations of the transverse position. However, as shown in Fig. 2(a), the preestablished z - x correlation from the pulse-front-tilted laser provides a geometric counterbalance. The dipole redistributes electrons horizontally according to their energy deviation ($x' \propto \delta$), but the initial z - x mapping ensures that longitudinal position remains linearly correlated with transverse coordinate, as depicted in Fig. 2(b).

Following dipole-induced phase-space conditioning, the electron beam enters the THz cavity and acquires energy modulation at the zero-crossing of the 0.3 THz field. As depicted in Fig. 2(c), the electron beam initially carries a positive energy chirp ($h = +15$ keV/ps). The THz interaction then imparts a spatially uniform energy shift $\delta = h_{\text{THz}}z$ with $h_{\text{THz}} = -43$ keV/ps, thereby flipping the chirp to $h = -28$ keV/ps, as illustrated in Fig. 2(d). In our simulations, the THz interaction is implemented using a 0.3 THz single-cycle pulse with an energy of 6 μJ coupled into a dielectric-lined waveguide structure similar to that used in existing THz-driven compression experiments [15].

Next, the dogleg compressor performs the required transverse-to-longitudinal emittance partitioning, as shown in Figs. 2(e) and 2(f). After the final drift, the THz-imposed

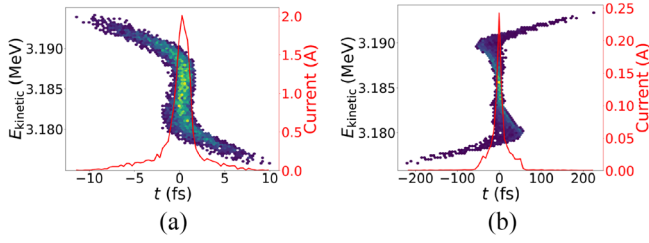


FIG. 4. Comparison of longitudinal phase space and current distributions: (a) multidimensional phase-space manipulation and (b) THz compression.

chirp is fully converted into temporal compression, realizing the phase-space transformation of Eq. (3), where the transverse dispersion maps divergence x' into longitudinal displacement $z_{\text{final}} = \eta x'$, as shown in Fig. 4(a). Given the transverse angular divergence $\sigma_{x'} = 3.15 \mu\text{rad}$ (rms) at the ADM beamline entrance, the theoretical bunch length is calculated as $\eta\sigma_{x'} \approx 600$ as. In simulation, the bunch duration is compressed to 810 as (rms) at the sample plane, while maintaining a 6 fC charge after collimation. Within the FWHM window, 76.4% of electrons are retained, demonstrating an efficient signal-to-noise ratio. The discrepancy between the simulation and the theoretical calculation arises from nonlinearities in the energy modulation.

After temporal compression, the electron beam develops transverse emittance anisotropy due to the asymmetric phase-space partitioning in the ADM section. The horizontal and vertical phase-space distributions decouple, producing a flat beam profile with increased horizontal divergence. To restore transverse symmetry, a skewed quadrupole doublet (Q1, Q2) is placed downstream of the dogleg, introducing controlled coupling between horizontal and vertical planes [23]. To clarify the transverse phase-space evolution during the compression process, we further compare the normalized projected transverse emittances at several representative locations. Before ADM compression, the beam is nearly symmetric in the transverse phase space, with $\epsilon_{nx} \approx 1.08 \times 10^{-8}$ and $\epsilon_{ny} \approx 1.08 \times 10^{-8}$. After ADM compression, a pronounced transverse anisotropy appears, with $\epsilon_{nx} \approx 1.69 \times 10^{-7}$ and $\epsilon_{ny} \approx 1.08 \times 10^{-8}$, indicating that the compression process introduces a substantial projected-emittance growth mainly in the bending plane. After the action of the rotated quadrupoles Q1 and Q2, the projected emittances at the sample plane become close again, with $\epsilon_{nx} \approx \epsilon_{ny} \approx 2.26 \times 10^{-8}$. This indicates that the transverse beam distribution at the sample plane becomes much more symmetric. Compared with the pre-ADM case, the projected emittance at the sample plane is about 2.09 times larger in both transverse directions. Simulations confirm that this active emittance control transforms the flat beam into a round beam with horizontal and vertical rms sizes of approximately $90 \mu\text{m}$ at the sample.

To benchmark the proposed compression method against conventional THz-driven longitudinal compression, we simulate the latter with identical beam and THz parameters, but without introducing pulse-front tilt in the drive laser. Consequently, the initial bunch duration is approximately 50 fs (rms). In a typical THz compression scenario, the modulated electron beam enters an overcompressed state after energy chirping, and a free drift allows tail electrons to catch up to the head, achieving full compression at the sample plane [15]. Under ideal conditions, the minimum bunch duration is determined by the product of longitudinal dispersion R_{56} and the slice energy spread σ_δ , expressed as $\sigma_z = R_{56} \cdot \sigma_\delta$. For the parameters $R_{56} = 4.1$ cm and $\sigma_\delta \approx 4.5 \times 10^{-5}$ (rms), this yields a theoretical duration of 6.1 fs (rms). Under identical beam and THz modulation conditions, simulations show that this approach compresses the bunch to 6.8 fs (rms) (also retaining 6 fC charge after collimation) and preserves only 48.8% of electrons within the FWHM temporal window, as shown in Fig. 4(b). No timing jitter is included in either case in Fig. 4(b), so this comparison is intended to isolate the intrinsic compression performance of the two schemes under identical static beam and THz parameters. Here, both schemes retain the same final charge of 6 fC after collimation. In the conventional THz compression case, the THz-induced modulation is only approximately linear near the bunch center, while electrons farther away from the center experience stronger higher-order nonlinear effects. After longitudinal phase-space rotation, these nonlinear components are converted into more pronounced leading and trailing temporal tails. In addition, the finite slice energy spread prevents all electrons from being compressed to exactly the same temporal focus. As a result, under the same retained charge of 6 fC, a larger fraction of the electrons remains distributed in the temporal tails rather than being concentrated in the compressed core, leading to a slightly longer pulse duration and a lower charge fraction within the FWHM temporal window. By contrast, the present scheme concentrates the retained charge more effectively in the compressed core, yielding a shorter pulse with weaker temporal tails.

To evaluate the stability and reproducibility of the proposed method under more realistic conditions, the stability analysis includes rf amplitude, rf phase, bunch charge, magnetic field, effective PFT-related, THz amplitude, and THz timing perturbations, all treated as statistically independent and applied simultaneously on a shot-to-shot basis. The laser-side contribution is represented by an effective PFT-related term that captures its leading influence on the cathode-imprinted spatiotemporal mapping. The effective PFT-related term is introduced to represent the leading fluctuation of the cathode-imprinted x - z mapping, including both a shift of the mapping center and a variation of the effective x - z coupling angle. The adopted 1% rms value therefore denotes a relative perturbation with respect to the ideal cathode-imprinted x - z

TABLE II. Jitter parameters and corresponding single-source timing jitter.

Jitter source	rms value	Timing jitter (rms)
rf amplitude	5×10^{-4}	688 as
rf phase	0.2 ps	224 as
Bunch charge	3%	280 as
Magnetic field	1×10^{-4}	197 as
Effective PFT-related term	1%	3.8 as
THz amplitude	1%	3.5 as
THz timing	300 as	180 as
All sources simultaneously	...	886 as

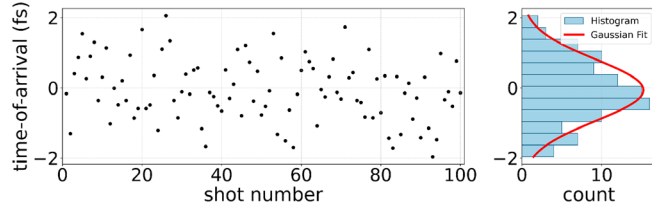


FIG. 5. Arrival-time jitter distribution across 100 consecutive shots for the multidimensional phase-space manipulation scheme.

correlation. The corresponding jitter parameters and single-source timing jitter are summarized in Table II.

Based on 100 consecutive shots, the compressed bunch remains in the attosecond regime, with a shot-to-shot bunch-length fluctuation of 22 as (rms) and an arrival-time jitter of 886 as (rms), as shown in Fig. 5. Single-source scans show that rf amplitude gives the largest contribution among the gun-related perturbations, whereas THz timing is the dominant contribution among the THz and laser-side perturbations. By comparison, the THz amplitude and effective PFT-related contributions remain much smaller under the present parameter set.

V. CONCLUSION

In summary, we have proposed a novel multidimensional phase-space manipulation approach that delivers robust attosecond-scale compression of MeV electron beams while minimizing timing jitter. Rather than relying solely on longitudinal dispersion (R_{56}) to convert energy spread into temporal compression, our method leverages transverse angular dispersion (η) as the primary driver, effectively exchanging transverse emittance for significantly tighter longitudinal compression. By combining pulse-front-tilted laser illumination at the photocathode, THz-driven energy chirping, and a transverse-longitudinal emittance-partitioning beamline, the proposed method compresses a 3.18 MeV electron beam from 747 fs (rms) to 810 as (rms) while maintaining a bunch-length fluctuation of 22 as (rms), an arrival-time jitter of 886 as (rms), and retaining 6 fC of charge. This represents nearly

an order-of-magnitude improvement over state-of-the-art two-dimensional manipulation schemes, accompanied by a substantial increase in transmitted charge. The multidimensional phase-space manipulation technique presented here paves the way for attosecond-resolved investigations of atomic and electronic dynamics in ultrafast science and has broad applicability to other accelerator-based sources that demand ultrashort electron pulses.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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