Analysis of Terahertz Driven MeV-UED Time Tool

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ABSTRACT

A relativistic electron beam interacting with a phase stable terahertz (THz) streaking pulse encodes temporal information into spatial beam profiles, improving timing precision for mega-electronvolt (MeV) ultrafast electron diffraction (UED) measurements. In this study, beam images collected at varied delays were analyzed to determine the correlation between transverse shift and THz phase, enabling arrival time retrieval with sub picosecond resolution. We investigated how different experimental parameters affected the magnitude of beam deflection recorded by a detector. The results show that THz streaking delivers greater precision than conventional arrival time monitoring methods, confirming its suitability for accurate time axis calibration in MeV-UED experiments and its value for advancing ultrafast structural dynamics studies.

1. INTRODUCTION

Ultrafast electron diffraction at megaelectronvolt energies provides atomic scale structural snapshots with femtosecond temporal resolution, enabling molecular movies of chemical dynamics[1]. Conventional radio frequency timing monitors can reduce arrival time jitter, but they introduce shot to shot energy variations and require large accelerator cavities, which limits both temporal precision and instrument compactness[1].

Terahertz streaking translates temporal information into a transverse spatial deflection, providing a compact and phase stable method for arrival time retrieval. Early demonstrations used single cycle THz pulses to compress relativistic electron bunches and achieved few hundred femtosecond resolution[2]. SLAC National Accelerator Laboratory's THz time tool has advanced this approach, enabling shot to shot arrival time tagging with sub 50 fs jitter suppression by calibrating THz phase against spatial shift[3].

Despite significant progress in THz based timing metrology, a systematic understanding of how key experimental parameters affect the magnitude of electron beam deflection, and thus timing precision, remains incomplete. Closing this gap is essential for improving the temporal resolution of MeV-UED electron cameras by providing a reliable reference for arrival time measurements.

In this work, we analyze data from an experiment that integrates SLAC National Accelerator Laboratory's terahertz time tool into a MeV-UED beamline, using the THz streaking pulse as a timing reference. We vary aperture structures and laser pump energies to quantify the resulting transverse beam deflection. By tracking beam centroids as a function of time, we retrieve the electron beam arrival time and characterize the effective bunch length along the beamline.

2. RELATED WORKS

Early demonstrations of THz-based temporal metrology in UED showed that single-cycle THz pulses can impart a transverse momentum kick to relativistic electron bunches, enabling velocity bunching and preliminary time-stamping capabilities[2]. Quasi–single-cycle THz pulses were integrated into a UED setup, improving temporal resolution from approximately 178 fs down to 85 fs without correction and to 5 fs with THz-based time stamping[2]. A dual-fed THz compression and streaking structure at SLAC achieved peak THz fields over 1.5 MV/cm with 3 MeV electron bunches, shot-to-shot bunch-length measurements near 40 fs, and jitter suppression across 1.3 ps delay scans[4]. The transverse spatiotemporal correlation imparted by various coupling geometries was quantified, establishing a calibration protocol for sub-50 fs timing-jitter suppression in single-shot measurements[3]. The performance of SLAC's THz time tool under user conditions was characterized by integrating aperture and detector geometries for real-time arrival-time diagnostics at up to 1 kHz and benchmarking contributions of beam emittance, bunch length, and detector point-spread function to timing uncertainty[4]. In this analysis, we focus specifically on how aperture structure and laser pump energy affect the measured electron beam deflection and, by extension, time-retrieval accuracy.

3. BACKGROUND

MeV scale ultrafast electron diffraction requires the generation of short electron pulses and their precise temporal control. A femtosecond ultraviolet laser produces pulses that liberate electrons from a photocathode, forming initial electron bunches. These bunches are accelerated in a radio frequency photogun to relativistic energies. Magnetic solenoids positioned along the beamline act as lenses to counteract space charge induced divergence and maintain beam focus. Phase stable terahertz pulses, generated by optical rectification in a nonlinear crystal, are coupled into the beam path using a split plate structure. A direct detection ePix camera records the resulting electron beam's impact on its sensors, providing single shot beam profile measurements. Synchronization of the UV laser, RF photogun, and THz source is achieved through a common timing reference to ensure consistent overlap of pulses.

4. EXPERIMENTAL SETUP

In the experiment, the UV laser drives electron emission from the photocathode, and the RF photogun accelerates the electrons to MeV energies. Downstream solenoids focus the beam before it intersects a phase stable, single cycle THz pulse in a split plate coupling structure. The THz field imparts a time dependent transverse momentum kick, encoding arrival time information as a spatial deflection. A delay stage varies the relative timing between the THz pulse and electron bunch over a picosecond scale window in fine steps, mapping temporal offsets to deflection shifts. The deflected beam impacts the ePix camera directly, which captures two dimensional beam profiles on a shot by shot basis. For a sample visual for one of the runs, please see Figure 4 located in Appendix A. Subsequent analysis tracks beam centroids versus delay to retrieve arrival times and assess how changes in aperture structure and laser pump energy influence the measured deflection.

5. DATA ANALYSIS

This experiment evaluated how aperture sizes and laser pump energy influence the measured transverse deflection of a relativistic electron beam during interaction with a phase stable THz streaking pulse. The aperture structures set the effective gap through which the THz field is coupled prior to overlap with the electron beam, so changing the aperture adjusts the local field distribution and coupling efficiency at the interaction point. A smaller micron scale aperture confines the THz mode more strongly, which can increase the field gradient sampled by the electrons and thus increase the time dependent transverse kick.

Figure 1 shows the center of mass trajectories of the electron beam as a function of delay for

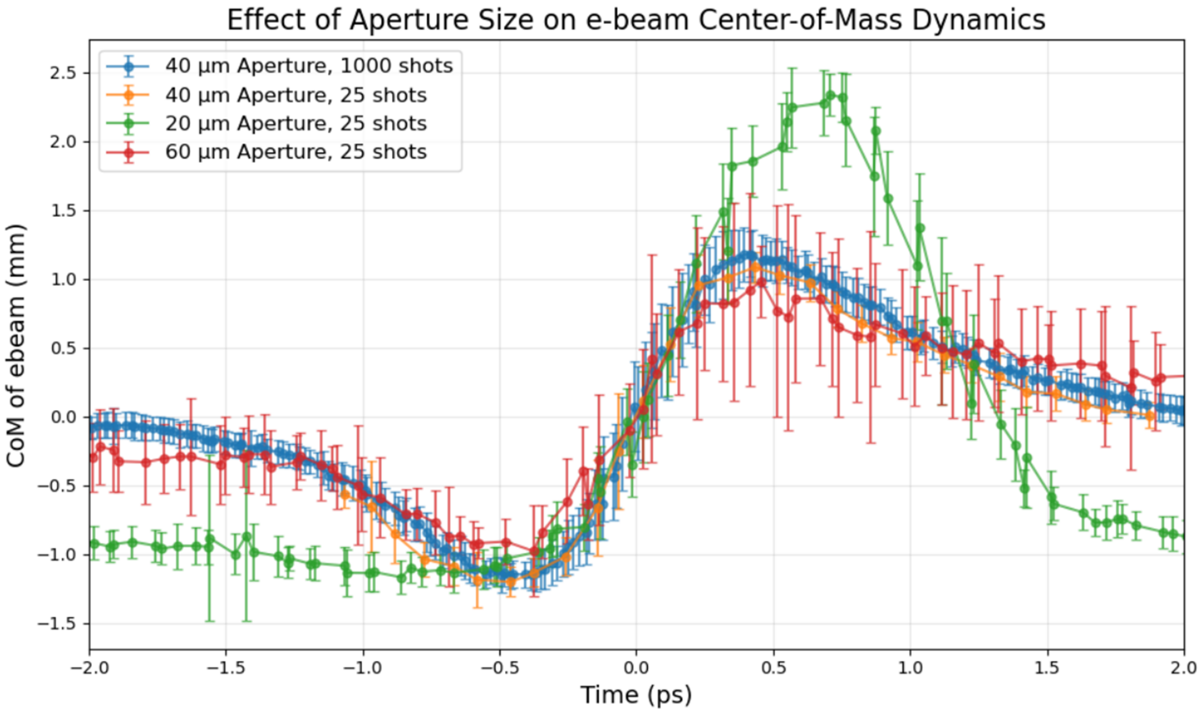

Figure 1: Deflection curves for different aperture configurations.

several aperture sizes. The 20 micrometer aperture produced the largest excursion of the beam center, indicating the strongest net deflection within the scanned delay range. The apparent steepness of each curve near the rising and falling edges reflects the local sensitivity of spatial deflection to time, so steeper segments correspond to larger deflection per unit delay. The error bars represent the shot to shot spread of the centroid measurement for each delay point. The data set with 1000 shots per delay exhibits visibly smaller error bars than those with 25 shots, consistent with reduced statistical uncertainty from increased averaging. This supports the practical conclusion that acquiring more shots per delay step improves the precision of the centroid estimate, thereby tightening the inferred time retrieval uncertainty.

The 60 micrometer aperture displays noticeably larger error bars across much of the scan, implying greater measurement variability for that particular aperture. Because the plotted uncertainties are standard deviations, the broader error bars point to either increased intrinsic deflection noise or reduced signal to noise in the centroid extraction for that case. Potential contributors include weaker effective THz coupling, larger spot size at the detector for that configuration, or enhanced sensitivity to alignment drifts; distinguishing among these would require follow up diagnostics, but the operational implication remains that larger apertures in this configuration yielded less precise deflection readouts.

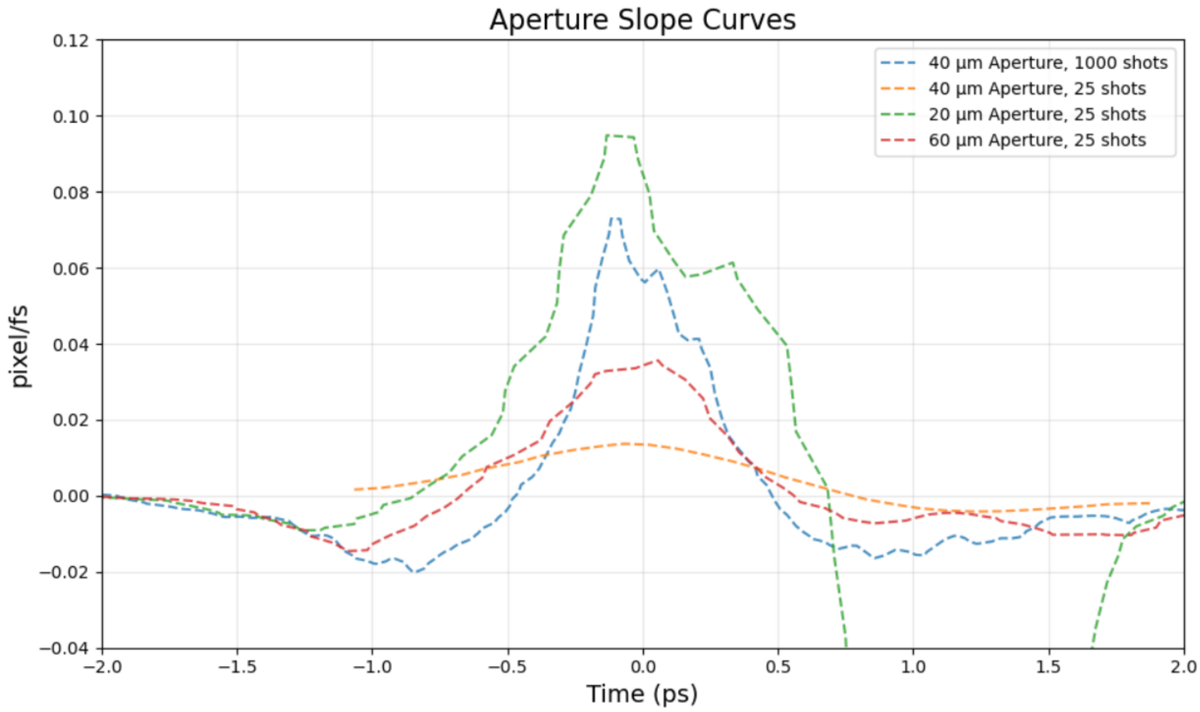

Figure 2: Slope of deflection versus delay for aperture variants.

Figure 2 presents the numerical slope of the deflection curves versus delay for each aperture. The slope traces emphasize the regions of maximum temporal sensitivity. The peak slopes cluster near the zero-crossings of the underlying THz field, where the streaking signal changes sign and the phase to position mapping is most linear. Operating near these zero-crossing regions maximizes the derivative, which improves timing sensitivity for a fixed spatial resolution at the detector. The figure also highlights a significant difference between two data sets taken with nominally identical 40 micrometer apertures. The set with more shots per delay yields a smoother and larger peak slope, while the lower shot count set shows a noisier, suppressed peak. This suggests that collecting substantially more than 25 shots per delay step can materially enhance the robustness of the slope estimate, reducing bias from noise and improving the effective timing precision.

The second parameter studied was the laser pump energy used to generate the THz pulse. Figure 3 shows a monotonic trend in which higher pump energies produce larger peak deflections. Because the streaking signal scales with the THz field amplitude, and the THz field typically increases with pump energy in the operating regime before saturation, the observed

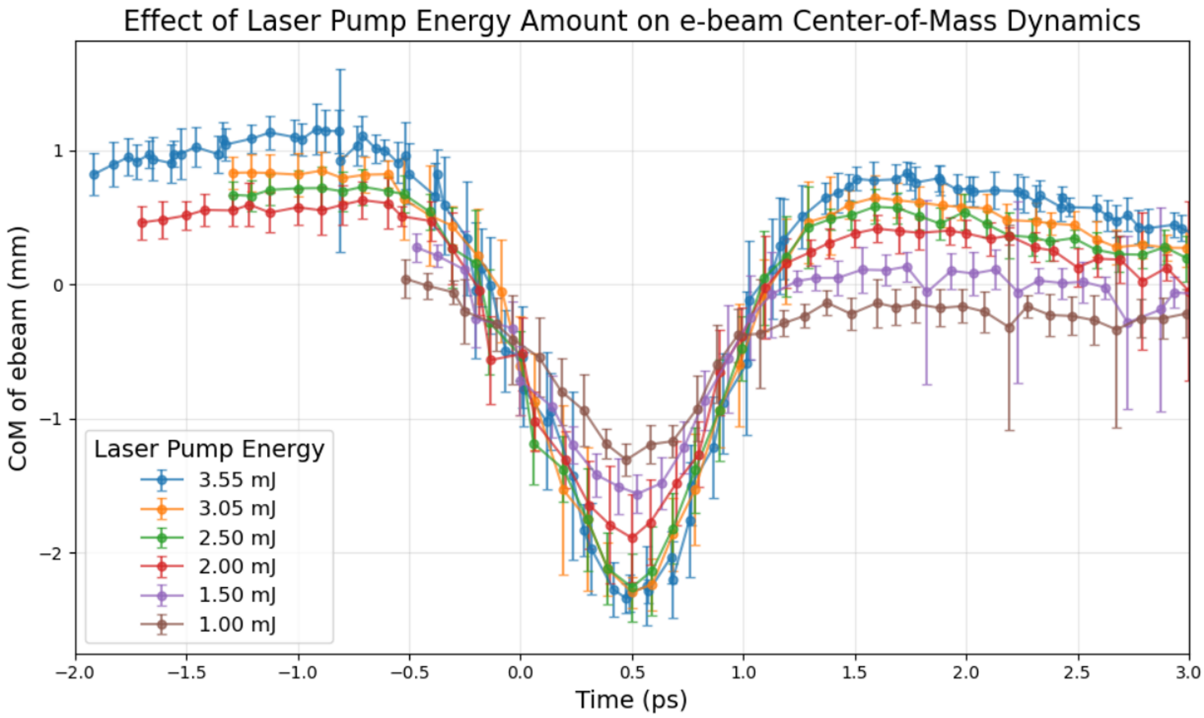

Figure 3: Deflection scaling with laser pump energy.

scaling is consistent with expectations. From a metrology standpoint, larger deflection amplitudes can expand the usable linear window around the zero-crossing and improve the signal to noise of centroid extraction; however, operation must remain within the linear response regime to avoid distortion in the phase to position mapping. A practical workflow that emerges is to tune the pump energy to the highest level that preserves linearity around the chosen operating phase, then maximize the number of shots per delay point to minimize shot to shot uncertainty.

Together, these analyses support three practical guidelines for THz streaking timing retrieval in MeV-UED. First, choose coupling geometries that concentrate the THz field at the interaction region; in this data set, smaller apertures produced larger deflection signals. Second, map the deflection as a function of delay to find and work near the region with the greatest slope, which is close to the THz zero-crossing; the interaction phase is set by the electron beam arrival, so it is identified from the observed deflection rather than prescribed for each shot. Third, record large shot ensembles at each delay to reduce statistical uncertainty, especially when estimating slopes and building local timing calibrations in the most linear region. These practices reduce arrival time retrieval uncertainty and yield a more reliable time axis for subsequent ultrafast measurements.

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REFERENCES

[1] E. C. Snively, M. A. K. Othman, M. Kozina, B. K. Ofori-Okai, S. P. Weathersby, *Femtosecond Compression Dynamics and Timing Jitter Suppression in a THz-driven Electron Bunch Compressor*, 2020.

[2] S. Weathersby, M. A. K. Othman, E. C. Snively, A. E. Gabriel, M. E. Kozina, X. Shen, F. Ji, S. Lewis, P. Vasireddy, D. Luo, X. Wang, M. C. Hoffmann, E. A. Nanni, *Visualizing Femtosecond Dynamics with Ultrafast Electron Probes through Terahertz Compression and Time-stamping*, 2021.

[3] M. A. K. Othman, A. E. Gabriel, E. C. Snively, M. E. Kozina, X. Shen, F. Ji, S. Lewis, S. P. Weathersby, P. Vasireddy, D. Luo, X. Wang, M. C. Hoffmann, E. A. Nanni, *Improved Temporal Resolution in Ultrafast Electron Diffraction Measurements through THz Compression and Time-stamping*, 2024.

[4] M. A. K. Othman, A. E. Gabriel, M. C. Hoffmann, F. Ji, S. Lewis, S. P. Weathersby, X. Wang, E. A. Nanni, *Terahertz Driven Compression and Time-Stamping Technique for Single-Shot Ultrafast Electron Diffraction*, 2021.

APPENDIX A

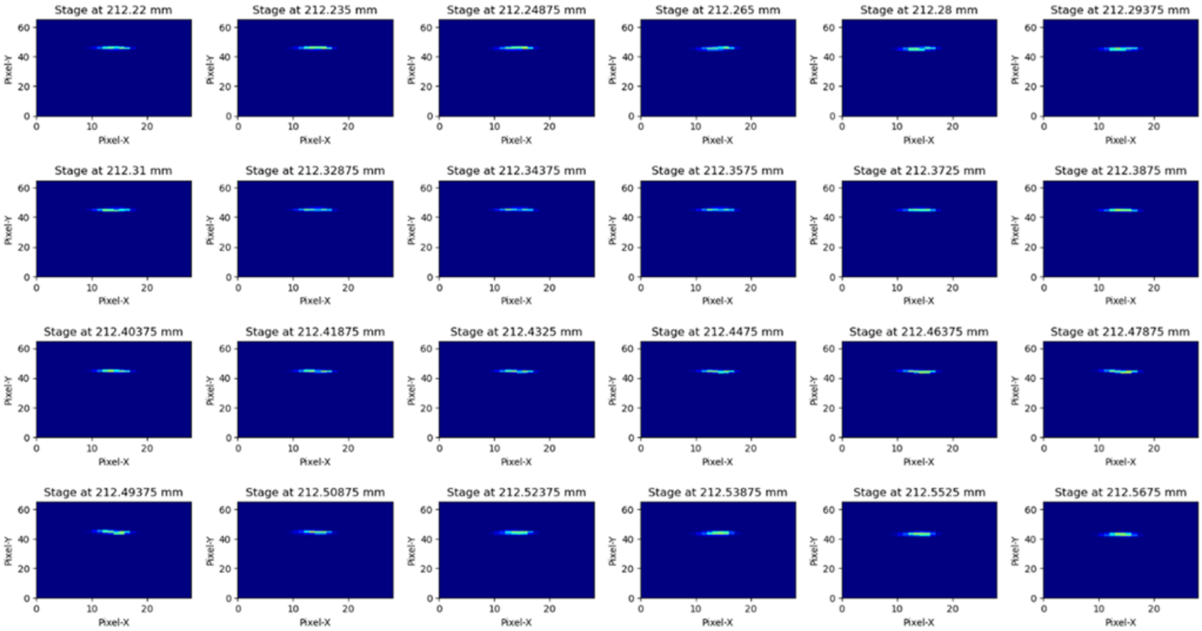

Figure 4: Average electron beam images across a scan of stage position from 212.22 to 212.6475 mm (left-to-right, top-to-bottom). Each panel shows the mean shot at the indicated position; axes are pixel coordinates and intensity is on a linear color scale.