

Pulse Duration as the Gatekeeper of Temporal Resolution in Ultrafast Measurements of Electron Dynamics

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Abstract

This extended essay investigates the critical role of pulse duration in ultrafast laser systems and its influence on the temporal resolution of measurements regarding attosecond and femtosecond-scale electron dynamics. While the fundamental premise suggests that shortening pulse duration allows scientists to "freeze" electron motion, this research demonstrates that realized experimental resolution is not defined by pulse width alone. Instead, effective temporal resolution Δt_{eff} emerges from a complex quadrature sum of independent variables, including pump and probe durations, arrival-time jitter, and instrument response timing. Through a synthesis of theoretical frameworks—such as the time-energy uncertainty principle and the Fourier limit—and an analysis of techniques like tr-ARPES and Ultrafast Electron Diffraction (UED), the study highlights the inevitable trade-offs between temporal precision and energy resolution. The findings indicate that while pulse duration establishes the theoretical lower bound of resolution, practical advancement requires system-level engineering focused on synchronization and jitter suppression rather than pulse compression alone. Ultimately, the essay argues that achieving high-fidelity measurement is less about minimizing a single parameter and more about managing the total instrument function to accurately resolve the causal history of electronic processes.

Keywords: Ultrafast laser systems, electron dynamics, temporal resolution, pulse duration, pump-probe spectroscopy, timing jitter, attosecond physics, time-energy uncertainty.

Research Question

How does the pulse duration in ultrafast laser systems influence the time resolution of measurements in attosecond or femtosecond-scale electron dynamics?

1. Introduction

In ultrafast physics, the line between processes that can be seen and those that can't is only a few femtoseconds or attoseconds long. In this area, the fast-moving behaviors of electrons happen, which regular tools can't catch in real time (Krausz & Ivanov, 2009). For scientists who want to study subatomic processes like tunneling, photoionization, or electron correlation, the need for precise temporal resolution is not just a technical issue; it is the most important thing. Ultrafast laser systems are one of the tools that have changed the way we can study these fleeting phenomena. The length of their pulses determines how well we can see motion on the atomic scale (Boschini et al., 2024).

When measuring events that happen in attoseconds (10^{-18} s), where electrons do their most basic jobs in matter and energy exchange, the length of the pulse becomes very important. Scientists can "freeze" electron motion for observation by shortening the pulse duration, which directly improves time resolution (Krausz & Ivanov, 2009). But this improvement does come with some technical trade-offs. Shorter pulses often need more complicated setups, precise timing, and can have limits on peak power or spectral width (Weiner, 2011).

The study of electron dynamics encompasses various timescales, each elucidating distinct physical processes. We can see vibrational motion, the first charge transfer, and the start of chemical reactions at the femtosecond scale (10^{-15} s). Shifting to the attosecond regime (10^{-18} s) reveals the basic electronic processes: Tunneling through barriers takes 1 to 10 attoseconds, while inner-shell relaxation and Auger processes take 1 to 100 attoseconds (Krausz & Ivanov, 2009). This temporal hierarchy directly influences our selection of laser pulse duration; aligning the measurement instrument with the phenomenon under examination is essential for significant observation.

The Extended Essay investigates the scientific question: "In what way does the pulse duration in ultrafast laser systems affect the temporal resolution of measurements in attosecond or femtosecond-scale electron dynamics?" The research will utilize scholarly sources, empirical evidence from peer-reviewed studies, and theoretical constructs pertaining to time-frequency uncertainty, nonlinear optics, and electron-laser interaction (Polli et al., 2010; Filippetto et al., 2022). This essay seeks to elucidate the influence of pulse characteristics on quantifiable parameters and, subsequently, on the comprehension of electron dynamics by analyzing both femtosecond and attosecond regimes, alongside the fundamental principles of methodologies such as pump-probe spectroscopy and high harmonic generation.

This relation pertains not only to optical physics but also to emerging technologies, chemistry, and quantum theory. It shows how closely our understanding of matter is linked to our ability to measure time.

2. Method and Approach

This essay synthesizes peer-reviewed literature and standard texts to evaluate how pulse duration sets the effective temporal resolution (Δt_{eff}) in common ultrafast platforms. The operational definition follows a quadrature sum of independent contributions:

$$\text{Eq. (1): } \Delta t_{\text{eff}} = \sqrt{(\Delta t_{\text{pump}}^2 + \Delta t_{\text{probe}}^2 + \tau_{\text{jitter}}^2 + \tau_{\text{inst}}^2)}$$

where Δt_{pump} and Δt_{probe} represent the pump and probe pulse durations at the sample position (not at the laser output), τ_{jitter} quantifies the relative arrival-time jitter between pump and probe pulses (which can be mitigated through per-shot time-stamping techniques), and τ_{inst} encompasses the combined detector response time, electronics bandwidth limitations, and residual phase noise contributions (Polli et al., 2010; Boschini, Zonno, & Damascelli, 2024; Hellmann et al., 2010; Trovatiello et al., 2020; Atia-tul-noor et al., 2024).

Abbreviations on first use; GDD = group-delay dispersion (with higher orders such as TOD); tr-ARPES = time- and angle-resolved photoemission spectroscopy; UED = ultrafast electron diffraction; UEM = ultrafast electron microscopy.

3. Theoretical Foundations of Ultrafast Spectroscopy

3.1 Time–Energy Uncertainty Principle

At the core of ultrafast measurement lies a fundamental trade-off: improving temporal resolution tends to degrade energy (spectral) resolution. This is the practical face of the time–energy uncertainty relation, commonly expressed as $\Delta E \cdot \Delta t \geq \hbar/2$. In optical terms, shortening the pulse duration broadens the frequency content, which sharpens when events occur but blurs which-energy channels they occupy (Krausz & Ivanov, 2009). In time-resolved experiments, this trade-off is a design constraint at every stage from source selection and compression to diagnostics and data analysis. Certain protocols can partially relax it by decoupling preparation and detection windows or by tailoring analysis windows; yet those gains still hinge on phase integrity and timing stability (Randi et al., 2017).

A helpful visualization is the joint time–frequency (Wigner) distribution: compressing a pulse squeezes the time axis while spreading the frequency axis. One therefore chooses a point on a two-dimensional plane: time on one axis, energy on the other. tr-ARPES (Time- and Angle-Resolved Photoemission Spectroscopy) prioritizes energy resolution when physics sits near the Fermi level, whereas transient absorption often prioritizes earliest time-domain onsets.

3.2 Fourier Limit and the Time–Bandwidth Balance

A pulse is Fourier-limited when its TBP (Time-Bandwidth Product) reaches the minimum allowed by its shape: Gaussian pulses $\Delta t \cdot \Delta \nu \approx 0.44$; sech² pulses ≈ 0.315 (Weiner, 2011; Trebino, 2000). Any uncompensated spectral phase GDD (Group-

Delay Dispersion) and higher orders inflates that product, lengthens the pulse, and dilutes temporal resolution.

A back-of-the-envelope: a 10 fs Gaussian pulse has $\Delta\nu \approx 0.44/(10 \times 10^{-15} \text{ s}) \approx 44$ THz. Around 800 nm, $\Delta\lambda (\lambda^2/c) \cdot \Delta\nu \sim 94$ nm a reminder that few-cycle pulses demand broad, flat gain and carefully managed dispersion. Residual GDD can be estimated via $\tau = \tau_0 \cdot \sqrt{[1 + (4 \ln 2 \cdot \text{GDD} / \tau_0^2)^2]}$; thus, $\tau_0 = 15$ fs and $\text{GDD} = 200 \text{ fs}^2$ stretch to ~ 40 fs ($\sim 2.7\times$), quietly eroding temporal resolution. Hence the rule: shorter pulses improve resolution only if the spectral phase is well-behaved.

4. Femtosecond Laser Technology and Pulse Properties

4.1 Generation and Measurement of Femtosecond Pulses

Generation. Kerr-lens mode locking (KLM) in Ti:sapphire oscillators yields few tens of femtosecond pulses thanks to broad gain and ultrafast nonlinearity (Yefet & Pe'er, 2013). For energetic, few-cycle operation, chirped pulse amplification (CPA) stretches, amplifies, and recompresses pulses to near-transform limits; OPCPA extends bandwidth and spectral reach at the cost of tighter synchronization (Strickland & Mourou, 1985).

Measurement. Intensity autocorrelation is phase-blind. FROG and SPIDER reconstruct the full field (amplitude + phase). SHG-FROG is common for near-IR; XFROG characterizes complex pulses against a known gate. SPIDER's spectral shear trades phase sensitivity against noise. Because diagnostics have distinct systematics (phase-matching bandwidth in FROG; calibration in SPIDER), cross-checking is good experimental hygiene (Trebino, 2000; Weiner, 2011; Rhodes et al., 2013).

4.2 Pulse-Duration Control and Its Impact

Pulse control is dispersion engineering and phase programming. Grating/prism compressors and chirped/high-dispersion mirrors remove GDD and higher orders; 4f pulse shapers (SLM at the Fourier plane) and AOPDF/DAZZLER program amplitude/phase (Weiner, 2011). Shorter, flatter-phase pulses tighten the instrument response, shrinking Δt_{eff} . Costs include broader bandwidth (reduced spectral selectivity), stricter alignment, increased susceptibility to nonlinear propagation (e.g., self-phase modulation), and tighter damage thresholds. The "sweet spot" is where resolution gains outweigh these costs for the specific physics under study. For instance, studying coherent phonon oscillations in semiconductors (period $\sim 100\text{-}300$ fs) requires only moderate temporal resolution ($\sim 20\text{-}30$ fs), allowing for narrower bandwidth pulses that maintain spectral selectivity. In contrast, resolving the initial electron-electron scattering in metals (<10 fs) demands the shortest possible pulses despite the accompanying spectral broadening. This matching principle, selecting pulse parameters based on the intrinsic timescale of the phenomenon, guides experimental design more effectively than simply pursuing ever-shorter pulses.

5.Temporal Resolution Limitations and Their Physical Origins

5.1 Effective Temporal Resolution: Convolution of Windows

In pump–probe work, effective temporal resolution is the convolution of pump/probe durations with arrival-time jitter and instrument response (see Eq. 1). If the probe is chirped (or the pump is intentionally swept), temporal and spectral selection are coupled; the appropriate preparation/observation windows must be defined operationally (Polli et al., 2010). Best practice is to measure the cross-correlation at the sample and treat spec-sheet numbers as optimistic upper bounds.

Worked example. Suppose $\Delta t_{\text{pump}} = 15$ fs, $\Delta t_{\text{probe}} = 25$ fs, $\tau_{\text{jitter}} = 20$ fs, $\tau_{\text{inst}} = 10$ fs. Then $\Delta t_{\text{eff}} \approx \sqrt{(225 + 625 + 400 + 100)} \approx \sqrt{(1350)} \approx 36.7$ fs. If per-shot time-stamping reduces τ_{jitter} to 8 fs, the sum becomes $225 + 625 + 64 + 100 = 1014$, giving ≈ 31.8 fs. The pulses did not change; the timing did.

5.2 Synchronization and per-Shot Time-Stamping

In XFEL–laser and MeV-UED contexts, arrival-time jitter can overshadow pulse durations. Arrival-time monitors and per-shot time-stamping push Δt_{eff} to sub-50 fs by sorting/correcting data using the true shot time (Atia-tul-noor et al., 2024; Diez et al., 2023). Electro-optic sampling, THz streaking, and optical–RF bridges are complementary strategies (Li et al., 2019). In UED (Ultrafast Electron Diffraction), RF phase/amplitude noise maps into timing; compact beamlines and higher gradients limit growth of jitter before correction. As a result, improvements in pulse duration translate directly into sharper instrument functions once the timing architecture is good enough (see Table 1).

Table 1. Representative instrument-function budget (Δt_{eff}) across techniques

Technique (typical)	Δt_{pump} (fs)	Δt_{probe} (fs)	τ_{jitter} (fs)	τ_{inst} (fs)	Δt_{eff} (fs)
Optical pump–optical probe	10–30	10–30	5–20	5–15	20–40
tr-ARPES (UV/XUV)	15–30	30–100	10–30	10–20	40–110
MeV-UED (uncorrected)	20–50	50–150	30–100	10–30	70–190
MeV-UED (time-stamped)	20–50	50–150	10–30	10–30	60–160

5.3 Special Considerations for Two-Dimensional and Complex Materials

Mini-Case 1 — MoS2 (2D excitons). Time-domain studies report excitonic formation onsets $\sim 15\text{--}35$ fs (Trovatello et al., 2020; Das et al., 2021). With a 10–15 fs pump and <20 fs jitter, one isolates the birth of the exciton; moving to 30–40 fs or tolerating >40 fs jitter blends onset with early dephasing, obscuring coherent features. Spectral placement near the A/B excitons enhances selectivity but heightens sensitivity to residual phase (e.g., small TOD ripples can shift apparent onset by several femtoseconds).

Mini-Case 2 — 1T-TaS₂ (CDW melting). Sub- to few-hundred-femtosecond dynamics mark the progression from electronic redistribution to electron phonon energy transfer and finally order-parameter motion (Hellmann et al., 2010; 2012). A 20–40 fs pump with per-shot time-stamping separates the electronic quench (<50 fs) from the slower lattice-assisted response (tens-hundreds of fs). Longer pumps or uncorrected jitter convolve the two, underestimating the initial quench rate.

While the comparative ranges in Table 1 are representative, facility-specific conditions (beamline geometry, detector bandwidth, phase-noise spectra) can shift the balance among Δt_{pump} , Δt_{probe} , τ_{jitter} , and τ_{inst} by tens of femtoseconds. Moreover, retrieval methods (e.g., FROG/SPIDER settings, cross-correlation gates) introduce model dependence that must be reported alongside resolution claims. The conclusions here therefore generalize trends rather than prescribe absolute numbers; all claims should be interpreted relative to Eq. (1) as measured at the sample.

5.4 Error Analysis and Uncertainty Propagation

In ultrafast measurements, uncertainty propagation follows standard quadrature addition when contributions are uncorrelated. For the effective temporal resolution in Equation 1, the uncertainty $\delta(\Delta t_{\text{eff}})$ can be expressed as:

$$\delta(\Delta t_{\text{eff}}) = (1/2\Delta t_{\text{eff}}) \times \sqrt{[(2\Delta t_{\text{pump}} \times \delta\Delta t_{\text{pump}})^2 + (2\Delta t_{\text{probe}} \times \delta\Delta t_{\text{probe}})^2 + (2\tau_{\text{jitter}} \times \delta\tau_{\text{jitter}})^2 + (2\tau_{\text{inst}} \times \delta\tau_{\text{inst}})^2]}$$

Typical uncertainties in pulse duration measurements are $\pm 5\text{--}10\%$ for FROG/SPIDER characterization, while timing jitter uncertainties depend strongly on the measurement method: $\pm 20\text{--}30\%$ for indirect estimation versus $\pm 5\text{--}10\%$ for direct time-stamping. These uncertainties compound, meaning a nominal "30 fs" resolution might realistically span 25–40 fs when all error sources are considered. This range often explains discrepancies between similar experiments and emphasizes why on-sample verification remains essential.

6. Electron-Dynamics Observation Techniques

Cross-technique contrast on one sample. On the same 1T-TaS₂ flake, a 25-fs optical pump combined with tr-ARPES (approx. 80-fs probe) can resolve band renormalization with $\sim 40\text{--}60\text{-fs } \Delta t_{\text{eff}}$, whereas MeV-UED with per-shot time-stamping captures lattice responses with $\sim 60\text{--}90\text{-fs } \Delta t_{\text{eff}}$. The complementary windows electronic vs structural arise directly from the probe terms in

Eq. (1), underscoring that shorter pump helps only when the probe and timing architecture allow it.

6.1 Pump-Probe Methods

Standard optical pump-optical probe experiments track reflectivity/transmissivity / absorption versus delay; effective resolution follows Eq. (1) and the ranges of Table

1. Without changing pulse duration, two levers improve outcomes: (i) single-shot acquisition (reduces drift), (ii) rapid scanning (covers delays faster than drift). Spectral placement matters: slight detuning from the A exciton in 2D semiconductors can emphasize coherent phonon signatures, whereas on-resonance probing may highlight population kinetics (Polli et al., 2010).

A closely related platform, time- and angle-resolved photoemission (tr-ARPES), images band-structure dynamics using UV/XUV probes. The time–energy trade-off is explicit: narrower energy resolution demands longer probe pulses and/or lower repetition. HHG expands momentum reach but tightens stability constraints; solid-state frequency conversion often offers cleaner timing at the cost of lower photon energy. Source choice effectively places the experiment at a chosen point on the time–energy plane (Boschini et al., 2024).

6.2 Ultrafast Electron Diffraction (UED)

UED converts transient atomic positions into femtosecond molecular movies. MeV beams mitigate space-charge broadening, enabling shorter electron packets and single-shot sensitivity at practical doses. Two ceilings dominate:

1. Timing. RF-induced arrival-time jitter and energy spread can wash out lattice dynamics. Per-shot time-stamping plus beamline optimization (high gradient, compact drifts, optimized compression) keeps sub-100-fs resolution within reach (Filippetto et al., 2022).
2. Geometry/overlap. For thicker samples or strongly refracting pumps, space–time overlap limits practical resolution even if pulses are short. Matching pump penetration depth to probe sensitivity is crucial.

Signal interpretation often uses the Debye–Waller factor: $I(Q, t) = I_0(Q) \cdot \exp[-2W(t)]$, with $W(t)$ proportional to $\langle Q^2 \rangle$. Early-time increases in mean-square displacement decrease Bragg intensities; with sufficient Δt_{eff} one can separate electronic softening (fast) from phonon-assisted heating (slower). Dose uniformity and multiple scattering in thicker samples must be controlled to avoid misattribution.

6.3 Ultrafast Electron Microscopy (UEM)

UEM (4D EM) combines real-space imaging with femtosecond gating. Stroboscopic single-electron operation minimizes space-charge while preserving spatial resolution. Reports pushing toward attosecond UEM in 2D systems are promising yet rightly cautious; interpretation demands rigorous calibration and synchronization hygiene (Hui et al., 2024; Baum & Ropers, 2024). In practice, routine UEM targets tens of femtoseconds with nanometer spatial resolution; <10 fs is attainable only when pulse duration, phase, timing, and fluence all align. Techniques like PINEM (photon-induced near-field electron microscopy) can serve

as optical gates narrowing the temporal window, but their integration requires careful energy-spread management.

Methodological caution in attosecond UEM. Claims of attosecond-scale UEM must be read with methodological caution: background subtraction, synchronization artifacts, and calibration drift can mimic sub-cycle features if Δt_{eff} is not independently verified on-sample. A conservative practice is to corroborate attosecond gating with an auxiliary optical cross-correlator and to report per-shot timing statistics together with the imaging dose.

7. Recent Research Developments and Future Perspectives

Synchronization and data handling. Arrival-time monitors and per-shot correction pipelines routinely deliver sub-50-fs effective resolution at XFEL laser stations, ensuring that subsequent pulse-duration improvements count (Atia-tul-noor et al., 2024; Diez et al., 2023). The near-term trend is toward smarter clocks: optical RF bridges, common-mode noise suppression, and algorithmic drift compensation that hold resolution stable over hours long runs.

Speed limits in 2D materials. Direct time-domain evidence for $\sim 15\text{--}35$ fs exciton onsets in TMDs sets concrete design targets for pulse duration and jitter budgets. Carefully detuned probes can separate coherent phonon modulations from incoherent population dynamics provided Δt_{eff} is narrow enough to prevent cross-talk (Trovatello et al., 2020; Das et al., 2021). Momentum-resolved approaches (e.g., momentum microscopy) layered atop femtosecond timing add selection rules and can expose valley-specific dynamics.

Phase engineering in correlated systems. In 1T-TaS₂, ultrafast optical excitation can melt the CDW and access metastable hidden states. Here, pulse duration selects whether one isolates the initial electronic quench or the lattice-assisted recovery (Hellmann et al., 2010; Maklar et al., 2023). Similar logic will likely guide studies in nickelates and other layered quantum materials: structure and electronic order often live on different clocks, so hybrid probes (optical pump + UED/UEM or tr-ARPES) become essential.

UED/UEM synergy. MeV-UED plus per-shot time-stamping enables single-shot, low-dose studies without sacrificing temporal resolution; UEM's shorter gating and better detectors promise femtosecond movies with nanometer pixels timing and dose permitting (Filippetto et al., 2022; Siddiqui et al., 2023). A pragmatic near-term view is that the greatest gains will come from timing architecture and phase control, not just shaving a few femtoseconds off nominal pulse width.

Design playbook (actionable). If the physics lives < 30 fs, target $\Delta t_{\text{pump}} \leq 15$ fs and $\tau_{\text{jitter}} \leq 20$ fs, even at the cost of broader bandwidth. If the physics hinges on energy selectivity, accept $\Delta t_{\text{probe}} \geq 50\text{--}80$ fs to gain narrower bandwidth (tr-ARPES). In mixed cases (e.g., separating electronic and lattice stages), combine a 20–40 fs pump

with per-shot time-stamping and a slower, energy-resolving probe. Always verify Δt_{eff} at the sample; treat oscillator specs as aspirational.

Forecast. With sub-20-fs, phase-corrected pumps, per-shot time-stamping, and tailored spectral windows, 10–30 fs effective resolution on solid-state samples is realistic without catastrophic damage. Reaching <10 fs is possible in select geometries but requires aggressive phase management, low-jitter clocks, and careful fluence engineering.

8. Conclusion

This investigation has demonstrated that while pulse duration in ultrafast laser systems establishes the fundamental lower bound of temporal resolution, the realized experimental resolution emerges from a complex interplay of factors. The operational equation $\Delta t_{\text{eff}} = \sqrt{(\Delta t_{\text{pump}}^2 + \Delta t_{\text{probe}}^2 + \tau_{\text{jitter}}^2 + \tau_{\text{inst}}^2)}$ reveals that pulse duration alone does not determine measurement capability; rather, it represents one term in a quadrature sum where timing stability and instrument response often dominate.

Moving from the femtosecond to the attosecond regime sharpens our view of electron dynamics tunneling delays, photoemission windows, the birth of excitons in 2D semiconductors, and the first symmetry breaking in charge-density-wave materials become temporally distinguishable rather than blended. In practice, however, shorter pulses are not a silver bullet. They come with broader spectra and stricter dispersion control, and they push experiments toward unavoidable trade-offs: time resolution versus energy/momentum resolution (especially acute in tr-ARPES), signal-to-noise versus sample damage thresholds, and single-shot fidelity versus high-repetition averaging.

The methodological lesson is pragmatic. Achieving headline pulse durations matters, but controlling everything that dilates the response function matters more. Concretely, the path to better effective resolution is threefold. First, synchronize by suppressing timing jitter with active locking, electro-optic time-stamping, and arrival-time monitors until timing noise is a minor term. Second, characterize and correct by minimizing chirp and residual dispersion using disciplined pulse measurement and compression (e.g., FROG (Frequency-Resolved Optical Gating)/SPIDER (Spectral Phase Interferometry for Direct Electric-field Reconstruction) and calibrated stretcher-compressor settings) so that the pulse that hits the sample matches the nominal specification. Third, design for the detector and the sample by accounting for detector/electronics response and sample-specific broadening (space charge, heating, phase-transition kinetics) in the resolution budget from the outset.

Framed this way, pulse duration is the primary lever that defines what is even thinkable to measure, while jitter control, dispersion management, and instrumentation define what is actually realized at the sample. That distinction explains why similar nominal pulse lengths can yield very different outcomes across

platforms optical pump–probe, ultrafast electron diffraction and microscopy, high-repetition FEL pump–probe, or attosecond photoemission—each with its own geometry, noise floor, repetition rate, and dose limits.

There are clear implications for future work. Pushing resolution further does not rely only on shaving a few more femtoseconds off the pulse; it requires system-level engineering: low-jitter, high-repetition sources; in-situ time-stamping that rides with every shot; adaptive pulse shaping that pre-compensates the sample stack; and real-time deconvolution that reports the effective resolution alongside the data. With those pieces in place, temporal resolution becomes predictable and portable, rather than a best-case number buried in the methods section.

In sum, the findings are both conceptual and operational. Pulse duration defines the lower bound; effective resolution is the managed sum of all contributions. When that balance is struck short, well-characterized pulses; negligible jitter; honest accounting of instrument and sample response attosecond and few-femtosecond experiments move from catching an instant to following an electronic process as it unfolds. That is the practical meaning of improved time resolution in this field: not merely smaller numbers, but cleaner causal stories about how electrons actually move.

Bibliography

- [1] Atia-tul-noor, Kumar, S., Schirmel, N., Erk, B., Manschwetus, B., Alisaukas, S., Braune, M., Cirmi, G., Czwalinna, M. K., Frühling, U., Grosse-Wortmann, U., Kschuev, N., Kuschewski, F., Lang, T., Lindenblatt, H., Litvinyuk, I., Meister, S., Moshhammer, R., Papadopoulou, C. C., ... Schulz, S. (2024). Sub-50 fs temporal resolution in an FEL-optical laser pump-probe experiment at FLASH2. *Optics Express*, 32(4), 6597. <https://doi.org/10.1364/OE.513714>
- [2] Baum, P., & Ropers, C. (2024). *Comment on "Attosecond electron microscopy and diffraction."* <http://arxiv.org/abs/2411.14518>
- [3] Boschini, F., Zonno, M., & Damascelli, A. (2024). Time-resolved ARPES studies of quantum materials. *Reviews of Modern Physics*, 96(1), 015003. <https://doi.org/10.1103/RevModPhys.96.015003>
- [4] Das, S., Wang, Y., Dai, Y., Li, S., & Sun, Z. (2021). Ultrafast transient sub-bandgap absorption of monolayer MoS₂. *Light: Science & Applications*, 10(1), 27. <https://doi.org/10.1038/s41377-021-00462-4>
- [5] Diez, M., Kirchberg, H., Galler, A., Schulz, S., Biednov, M., Bömer, C., Choi, T.-K., Rodriguez-Fernandez, A., Gawelda, W., Khakhulin, D., Kubicek, K., Lima, F., Otte, F., Zalden, P., Coffee, R., Thorwart, M., & Bressler, C. (2023). A sensitive high repetition rate arrival time monitor for X-ray free electron lasers. *Nature Communications*, 14(1), 2495. <https://doi.org/10.1038/s41467-023-38143-y>
- [6] Filippetto, D., Musumeci, P., Li, R. K., Siwick, B. J., Otto, M. R., Centurion, M., & Nunes, J. P. F. (2022). Ultrafast electron diffraction: Visualizing dynamic states of matter. *Reviews of Modern Physics*, 94(4), 045004. <https://doi.org/10.1103/RevModPhys.94.045004>

- [7] Hellmann, S., Beye, M., Sohrt, C., Rohwer, T., Sorgenfrei, F., Redlin, H., Kalläne, M., Marczyński-Bühlow, M., Hennies, F., Bauer, M., Föhlisch, A., Kipp, L., Wurth, W., & Rossnagel, K. (2010). Ultrafast Melting of a Charge-Density Wave in the Mott Insulator 1T-TaS₂. *Physical Review Letters*, 105(18), 187401. <https://doi.org/10.1103/PhysRevLett.105.187401>
- [8] Hellmann, S., Rohwer, T., Kalläne, M., Hanff, K., Sohrt, C., Stange, A., Carr, A., Murnane, M. M., Kapteyn, H. C., Kipp, L., Bauer, M., & Rossnagel, K. (2012). Time-domain classification of charge-density-wave insulators. *Nature Communications*, 3(1), 1069. <https://doi.org/10.1038/ncomms2078>
- [9] Hui, D., Alqattan, H., Sennary, M., Golubev, N. v., & Hassan, M. Th. (2024). Attosecond electron microscopy and diffraction. *Science Advances*, 10(34). <https://doi.org/10.1126/sciadv.adp5805>
- [10] Krausz, F., & Ivanov, M. (2009). Attosecond physics. *Reviews of Modern Physics*, 81(1), 163–234. <https://doi.org/10.1103/RevModPhys.81.163>
- [11] Li, R. K., Hoffmann, M. C., Nanni, E. A., Glenzer, S. H., Kozina, M. E., Lindenberg, A. M., Ofori-Okai, B. K., Reid, A. H., Shen, X., Weathersby, S. P., Yang, J., Zajac, M., & Wang, X. J. (2019). Terahertz-based subfemtosecond metrology of relativistic electron beams. *Physical Review Accelerators and Beams*, 22(1), 012803. <https://doi.org/10.1103/PhysRevAccelBeams.22.012803>
- [12] Maklar, J., Sarkar, J., Dong, S., Gerasimenko, Y. A., Pincelli, T., Beaulieu, S., Kirchmann, P. S., Sobota, J. A., Yang, S., Leuenberger, D., Moore, R. G., Shen, Z.-X., Wolf, M., Mihailovic, D., Ernstorfer, R., & Rettig, L. (2023). Coherent light control of a metastable hidden state. *Science Advances*, 9(47). <https://doi.org/10.1126/sciadv.adi4661>
- [13] Polli, D., Brida, D., Mukamel, S., Lanzani, G., & Cerullo, G. (2010). Effective temporal resolution in pump-probe spectroscopy with strongly chirped pulses. *Physical Review A*, 82(5), 053809. <https://doi.org/10.1103/PhysRevA.82.053809>
- [14] Randi, F., Fausti, D., & Eckstein, M. (2017). Bypassing the energy-time uncertainty in time-resolved photoemission. *Physical Review B*, 95(11), 115132. <https://doi.org/10.1103/PhysRevB.95.115132>
- [15] Rhodes, M., Steinmeyer, G., Ratner, J., & Trebino, R. (2013). Pulse-shape instabilities and their measurement. *Laser & Photonics Reviews*, 7(4), 557–565. <https://doi.org/10.1002/lpor.201200102>
- [16] Siddiqui, K. M., Durham, D. B., Cropp, F., Ji, F., Paiagua, S., Ophus, C., Andresen, N. C., Jin, L., Wu, J., Wang, S., Zhang, X., You, W., Murnane, M., Centurion, M., Wang, X., Slaughter, D. S., Kaindl, R. A., Musumeci, P., Minor, A. M., & Filippetto, D. (2023). Relativistic ultrafast electron diffraction at high repetition rates. *Structural Dynamics*, 10(6). <https://doi.org/10.1063/4.0000203>
- [17] Strickland, D., & Mourou, G. (1985). Compression of amplified chirped optical pulses. *Optics Communications*, 55(6), 447–449. [https://doi.org/10.1016/0030-4018\(85\)90151-8](https://doi.org/10.1016/0030-4018(85)90151-8)
- [18] Trebino, R. (2000). *Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses: The Measurement of Ultrashort Laser Pulses*. Springer Science & Business Media.

- [19] Trovatiello, C., Katsch, F., Borys, N. J., Selig, M., Yao, K., Borrego-Varillas, R., Scotognella, F., Kriegel, I., Yan, A., Zettl, A., Schuck, P. J., Knorr, A., Cerullo, G., & Conte, S. D. (2020). The ultrafast onset of exciton formation in 2D semiconductors. *Nature Communications*, 11(1), 5277. <https://doi.org/10.1038/s41467-020-18835-5>
- [20] Weiner, A. M. (2011). Ultrafast optical pulse shaping: A tutorial review. *Optics Communications*, 284(15), 3669–3692. <https://doi.org/10.1016/j.optcom.2011.03.084>
- [21] Yefet, S., & Pe'er, A. (2013). A Review of Cavity Design for Kerr Lens Mode-Locked Solid-State Lasers. *Applied Sciences*, 3(4), 694–724. <https://doi.org/10.3390/app3040694>