Q 26: Poster – Ultrashort Pulses and Strong Fields (joint session K/Q)

Time: Tuesday 17:00–19:00 Location: Philo 1. OG

Q 26.1 Tue 17:00 Philo 1. OG

Theoretical prediction of vibrational effects in multi-photon spectroscopy — •herve tajouo tela, deshan li, and julien bloino — Scuola Normale Superiore Pisa, Italy

The numerical investigation of molecular optical properties is essential for advancing our understanding of light*matter interactions. In this work, we present computational approaches for modeling two- dimensional (2D) photon absorption processes, with a particular focus on benchmarking 2D electronic*electronic transitions. These benchmark studies establish a basis for extending the methodology to more general frameworks that incorporate electronic*vibrational coupling. By employing advanced numerical techniques and high-precision algorithms, we aim to achieve accurate simulations of nonlinear optical responses and to predict spectroscopic signatures in complex molecular systems. Ultimately, this work seeks to improve the reliability of numerical simulations in capturing the fundamental features of multiphoton absorption processes, with applications spanning spectroscopy, photophysics, and quantum dynamics.

Q 26.2 Tue 17:00 Philo 1. OG

A Flexible Laser Micromachining Platform for Fabricating Integrated Photonic Systems in Transparent Materials — •Yassin Nasr, Patrick Hildebrand, Veronica Montoya, Thilo Danner, Andreas Michalowski, and Tobias Menold — University of Stuttgart - Institut für Strahlwerkzeuge (IFSW), Stuttgart, Germany

The increasing demand for compact, robust, and fully integrated photonic systems requires fabrication tools that can structure transparent materials with high precision and three-dimensional flexibility. Many established laser micromachining studies rely on highly specialized setups optimized for a single process, limiting systematic comparisons and slowing scientific progress. To overcome these constraints, we developed a laser micromachining platform that combines multiple ultrafast laser processes into one versatile system architecture.

The setup combines a high-NA microscope objective for generating micrometer-scale focal spots, a galvanometric scanner and a high-precision XYZ translation stage for dynamic 3D processing and a spatial light modulator (SLM) for dynamic correction of aberrations and controlled beam shape inside transparent materials.

This architecture enables scientific investigations of various laser-based micromachining processes like direct laser writing of waveguides, selective laser etching to create integrated microstructures like lenses and laser-assisted bonding for joining glass substrates. All these processes form the technological basis for the scalable fabrication of robust integrated photonic systems on one single manufacturing platform.

Q 26.3 Tue 17:00 Philo 1. OG

Spatiotemporal analysis of non-collinear optical parametric oscillators — •Robin Mevert[1,2], Fridolin Jakob Geesmann[1], Oliver Melchert[1,2], Han Rao[1,2], Arun Paudel[1,2], and Uwe Morgner[1,2,3] — [1]Leibniz University Hannover, Institute of Quantum Optics, Hannover, Germany — [2]Cluster of Excellence PhoenixD, Hannover, Germany — [3]Laser Zentrum Hannover e.V., Hannover, Germany

Femtosecond non-collinear optical parametric oscillators exhibit complex spatiotemporal dynamics, making it challenging to predict their steady-state under different input conditions. This study applies a GPU-accelerated 2D+1-dimensional split-step Fourier method to solve a generalized model of the coupled wave equations. It considers all potential second-order nonlinear mixing processes, including phase matching, diffraction, and walk-off, for all interacting pulses. Additionally, the model includes the impact of third-order nonlinear effects, such as self-phase modulation (SPM) and cross-phase modulation (XPM), on the resulting cavity mode. The cavity roundtrip is modelled using the Collins diffraction integral, with additional losses, dispersion, and spatial filtering due to the limited size of the mirrors.

Q 26.4 Tue 17:00 Philo 1. OG

Dressed-state-enhanced harmonic generation at high intensities with a single driving field — •Oskar Ernst and Thomas Halfmann — TU Darmstadt, Institut für angewandte Physik, Darmstadt, Germany

We investigate 5th and 7th harmonic generation of ultrashort picosecond laser pulses in the vacuumultraviolet (VUV) regime, enhanced by laser-induced dressed states in xenon. The pump laser for harmonic generation simultaneously acts as a control field, preparing multiple dressed states with large Autler-Townes splittings in the terahertz range. We observe well-defined dressed states even at large intensities up to 30 TW/cm^2, corresponding to an already small Keldysh parameter around 2. The presence of dressed states compensates the Stark shift, enabling resonantly enhanced frequency conversion by up to one order of magnitude across a broad spectral window of approximately 40 nm, tunable via laser wavelength and intensity. Our results demonstrate that significant resonance enhancements of VUV generation via dressed states are possible and relevant even without an additional control field.

Q 26.5 Tue 17:00 Philo 1. OG

Time-Trapping Towards Manipulation of Single-Photon Wavepackets — •Marvin Franzke[1], Fridolin Geesman[1], David Zuber[1,2], Ihar Babushkin[1,2,3], and Uwe Morgner[1,2] — [1]Leibniz University Hannover, Institute of Quantum Optics, Welfengarten 1, 30167 Hannover, Germany — [2]Cluster of Excellence PhoenixD (Photonics, Optics, and Engineering-Innovation Across Disciplines), 30167 Hannover, Germany — [3]Max Born Institute, Max-Born-Straße 2a, 10117 Berlin, Germany

In this project we are going to demonstrate experimentally a recent, theoretically suggested way of trapping and manipulating femtosecond-long weak pulses. A soliton propagating in a gas-filled hollow-core fiber creates a refractive index potential capable of trapping a much weaker pulse or even single photons. A weak pulse, described by linear optics, would always undergo dispersion, but trapping inside a soliton, described by nonlinear optics, allows for a dispersion-free propagation. Furthermore, trapping allows manipulation of the weak pulse by manipulating the soliton trap, since the weak pulse follows adiabatically. Here, two components of the experimental setup are discussed: an optical parametric amplifier (OPA) delivering the pulses, and diffractive optical elements (DOEs) converting the Gaussian mode from the OPA to higher order modes. These higher order modes are a crucial feature because the soliton and the weak pulse are at different wavelengths. By choosing different higher order modes for them and tuning the gas pressure, group velocity matching can be achieved. Furthermore, theoretical considerations about time-trapping are presented.

Q 26.6 Tue 17:00 Philo 1. OG

Towards All-Optical Attoclock Measurements in Noble Gases Using Short-Wave Infrared Laser Pulses — •Fridolin Geesmann[1], Morten Drees[2], David Zuber[1,3], Ihar Babushkin[1,3,4], and Uwe Morgner[1,3] — [1]Leibniz University Hannover, Institute of Quantum Optics, Hannover, Germany — [2]University of Ottawa, Ottawa, Canada — [3]Cluster of Excellence PhoenixD, Hannover, Germany — [4]Max Born Institute, Berlin, Germany

Laser driven ionization of noble gases gives rise to a plethora of interesting effects, such as the so-called Brunel radiation, which originates from the ionization and subsequent acceleration of electrons in the strong optical electric field. The study of this radiation, in particular of its polarization state, allows for detailed insights into the fundamental principles of light-matter interaction. Here, we report on the usage of elliptically polarized short-wave infrared femtosecond laser pulses generated by a home-built optical parametric amplifier to drive the generation of Brunel harmonics in Argon, which then encode information about the tunnel time of the electrons through the Coulomb barrier of the gas atoms in the rotation of their polarization ellipse. Our setup facilitates ultrashort laser pulses centered around 2 μm that exhibit pulse energies of up to 110 μJ and pulse durations below 40 fs. Furthermore, it allows for the simultaneous measurement of the intensity-dependent polarization state of the third and fifth harmonic from the Brunel field, thus enabling an all-optical characterization of the tunnelling time of the matter under test.

Q 26.7 Tue 17:00 Philo 1. OG

Probing High-Order Susceptibilities of monolayer MoS_2 via High Harmonic Generation: TDDFT approach — •Yeganehsadat Alvankar[1,2], Elnaz Irani[2], Hamid Talkhabi[1,2], and Mohammad Monfared[3] — [1]3ICMM, Centro Superior de Investigaciones Cientficas, Sor Juana Ines de la Cruz, 3 Cantoblanco, 28049 Madrid, Spain — [2]Department of Physics, Faculty of Basic Sciences, Tarbiat Modares University, P.O. Box 14115-175, Tehran, Iran — [3]Institute of Theoretical Physics, Leibniz University Hannover, Appelstraße 2, 30167 Hannover, Germany

High-harmonic generation (HHG) is a powerful method for probing high-order nonlinear optical responses in solids, across both perturbative and non-perturbative regimes.

Here, we use time-dependent density functional theory (TDDFT) to compute the nonlinear susceptibilities ($\chi^{(5)}, \chi^{(7)}, \chi^{(9)}$) of monolayer MoS_2 via HHG. Simulations employ intense ultrafast laser pulses ($\lambda_0 = 600, \text{nm}$) with peak intensities from 0.2-1.2 TW/cm^2.

Our results exhibit power-law scaling $\text{Yield}_N = A_N I^N$ and interband polarization, enabling direct extraction of higher-order susceptibilities. We also observe strong crystal orientation dependence, with anisotropic behavior across harmonic orders, emphasizing the role of polarization control in 2D material characterization.

Unlike previous methods (e.g., attosecond streaking) that inferred lower-order susceptibilities indirectly, HHG directly reveals higher-orders responses without broad spectra or indirect analysis. Quantifying such nonlinearities is key to advancing ultrafast photonic.

Q 26.8 Tue 17:00 Philo 1. OG

Neural network reconstruction of hamiltonians and transition dipole couplings from transient absorption spectra — •Ronald Cardenas, Ulf Saalmann, and Jan-Michael Rost — MPI-PKS, Dresden, Germany

Transient absorption spectroscopy (TAS) provides insight into ultrafast electronic dynamics, yet the resulting spectra are often challenging to interpret with conventional tools. In this work, we develop a Convolutional Neural Network (CNN) that reconstructs effective Hamiltonian matrices directly from TAS data. In addition to recovering effective energy levels, the model also predicts transition dipole couplings, which determine electronic coherences and state interactions under external fields. These couplings are essential to determine the optical response for linear and nonlinear optical processes. As they cannot be measured directly, they are typically obtained from ab initio calculations. Such calculations can become demanding for larger systems or situations involving many excited states. The CNN approach provides an alternative route to estimating these couplings using only spectroscopic input. The reconstructed Hamilton matrices enable the calculation of dynamical properties such as time-dependent dipole moment and polarization response. They can also be used for simulations of open-system Lindblad dynamics, coherent control schemes, nonlinear spectroscopy, and strong-field ionization models. Overall, our approach links experimental TAS data to the theoretical parameters needed to model ultrafast light*matter interactions, offering a flexible framework for complex molecular systems.

Q 26.9 Tue 17:00 Philo 1. OG

Neural network reconstruction of hamiltonians and transition dipole couplings from transient absorption spectra — •Ronald Cardenas, Ulf Saalmann, and Jan-Michael Rost — MPI-PKS, Dresden, Germany

Transient absorption spectroscopy (TAS) provides insight into ultrafast electronic dynamics, yet the resulting spectra are often challenging to interpret with conventional tools. In this work, we develop a Convolutional Neural Network (CNN) that reconstructs effective Hamiltonian matrices directly from TAS data. In addition to recovering effective energy levels, the model also predicts transition dipole couplings, which determine electronic coherences and state interactions under external fields. These couplings are essential to determine the optical response for linear and nonlinear optical processes. As they cannot be measured directly, they are typically obtained from ab initio calculations. Such calculations can become demanding for larger systems or situations involving many excited states. The CNN approach provides an alternative route to estimating these couplings using only spectroscopic input. The reconstructed Hamilton matrices enable the calculation of dynamical properties such as time-dependent dipole moment and polarization response. They can also be used for simulations of open-system Lindblad dynamics, coherent control schemes, nonlinear spectroscopy, and strong-field ionization models. Overall, our approach links experimental TAS data to the theoretical parameters needed to model ultrafast light-matter interactions, offering a flexible framework for complex molecular systems.

Q 26.10 Tue 17:00 Philo 1. OG

Open-shell electron dynamics with restricted open-shell configuration interaction singles — •ka hei lee[1,2], pascal krause[1], and annika bande[1,2] — [1]Inorganic Chemistry Institute, Leibniz University Hannover, Germany — [2]Theory of Electron Dynamics and Spectroscopy, Helmholtz-Zentrum Berlin, Germany

The description of correlated, ultrafast electron dynamics in polyatomic many-electron molecules is a challenging task. The time-dependent configuration interaction (TDCI) method has shown to correctly describe the light-induced excitation processes on the natural time scale of the electrons. By employing atom-centered basissets formed spin orbitals, monitoring the evolution of the electronic wave packet in TDCI framework becomes possible and analysis tools of the electron-hole-pair formation are available. [1, 2]

The study of dynamics of open-shell systems states an even bigger challenge as it requires a multi-configurational character for the spin-adapted wavefunction. In this poster, I present how the time-dependent restricted open-shell configuration interaction singles (TD-ROCIS) methods can be employed to monitor light-driven electron dynamics calculations for open-shell systems.

[1] F. Langkabel, P. A. Albrecht, A. Bande, P. Krause, Chem. Phys., 557, 111502 (2022)

[2] F. Langkabel, P. Krause, A. Bande, WIREs Comput Mol Sci., 14, e1696 (2024)

Q 26.11 Tue 17:00 Philo 1. OG

Impact of vertical Lidar misalignment on turbulence characterization for wind energy applications — •Vidana Popkova[1], Florian Jäger[1,2], Lukas Pauscher[1,2,3], Fabian Spallek[1], and Stefan Yoshi Buhmann[1] — [1]University of Kassel, Germany — [2]Fraunhofer IEE, Kassel, Germany — [3]Vrije Universiteit Brussel, Belgium

To evaluate the quality of possible wind-park locations, accurate knowledge of the turbulence characteristics of the expected wind-velocity-field is essential. The turbulence properties are commonly described by the variance of the field and may be extracted from measurements or simulations. Multi-LiDAR (Light Detection And Ranging) setups offer precise measurements for determining turbulence properties, but some systematic measurement uncertainties remain hard to control for. In particular, vertical offsets between LiDAR beams can drastically bias derived variances due to the large impact of the beam configuration on the measured data. We use a modified Mann model [1] to calculate the turbulence properties based on the spectral tensor and simulate dual-LiDAR configurations to study the influence of vertical offsets on the resulting variances. To this end, we introduce offsets directly in the spectral domain and examine their impact for varying atmospheric parameters. Several significant beam configurations are analyzed and compared with data from long-term mast measurements. The resulting theoretical framework can subsequently be used to develop turbulence-correction methods for misaligned LiDAR setups.

[1] Mann, J., J. Fluid Mech., 273, 141-168 (1994).

Q 26.12 Tue 17:00 Philo 1. OG

Methods and hurdles for a live shot to shot polarization diagnostic — •Moritz Mogilowski[1,2] and Markus Illchen[1,2] — [1]Universität Hamburg, Hamburg, Germany — [2]CFEL, Hamburg, Germany

With the recent advances of free electron lasers, pushing further into the attosecond time regime with ultra short pulses investigation of the chirality and and its time dependence on electronic movements is becoming feasible. The polarization of the FEL pulse is critical and its charactisation is not only important for analysing the data but also an important live metric for the machine operators. In this poster a robust and flexible approach to a shot based live polarization diagnostic based on almost intrusion free electron time of flight spectroscopy is shown. Common failures and their remedies are also discussed.

Q 26.13 Tue 17:00 Philo 1. OG

A Lab-based High Brilliance Secondary Source for Hard X-ray Generation — •Lion Günster, Luka Petersen, Jose Mapa, Greta Paruschke, Philip Mosel, Sven Fröhlich, Andrea Trabattoni, Uwe Morgner, and Milutin Kovacev — Leibniz Universität Hannover - Institut für Quantenoptik, Hannoverm Deutschland

The development of high-brilliance X-ray sources is one of the key factors driving rapid progress in industrial and medical applications. Due to the limitations of conventional X-ray sources, this growing demand

has stimulated research into laser-based secondary sources. Combined with very high-power-laser, very promising results have already been reported. Within the framework of the XProLas project we construct and test such a laser-produced plasma X-ray source for their usability in industrial applications.
Femtosecond pulses with a pulse energy of 10 mJ are focused on a copper wire target reaching laser intensities of $2 * 10^{18}\,\mathrm{W/cm^2}$. To enable continuous operation of the source multiple debris mitigation schemes have been implemented. With a repetition rate of 50 kHz we aim to achieve brilliance levels of over $5 * 10^{13}$ photons/s sr in Cu K_α, surpassing state-of-the-art conventional X-ray sources by one order of magnitude.

Q 26.14 Tue 17:00 Philo 1. OG

New light in the lab for single-particle imaging experiments — •Jasper Boultwood[1], Indrani Dey[1], Frederic Ussling[1], José Gómez Torres[1], Yves Acremann[2], Alessandro Colombo[1], Linos Hecht[1], Isabelle Bollier[1], Ehsan Hassanpour Yesagi[1], Jannis Lehmann[2], Katharina Kolatzki[1], Mirjam Kunz[1], Mario Sauppe[1], Angela Vidoni[1], Simon Wächter[1], Björn Senfftleben[1], and Daniela Rupp[1] — [1]Nanostructures and Ultrafast Science, ETH Zürich — [2]D-PHYS, ETH Zürich

Lab-based coherent diffraction imaging (CDI) of free-flying isolated nanoparticles has only recently become feasible and opens up new research opportunities. Short-wavelength pulses focused to high intensities are required, which are connected to rather extreme conditions for the high-harmonic generation (HHG) process. We investigate the use of different focusing geometries and driving wavelengths to optimize XUV pulse generation from a high-power NIR laser amplifyer (800 nm, 20 mJ, 30 fs). Interestingly, XUV generation in a Xenon gas cell using a 400 nm driving wavelength from second harmonic generation (SHG) in a BBO crystal results in the production of a single harmonic instead of four harmonics typical for an 800 nm driver. This single-line output is of interest for CDI applications as monochromatic diffraction creates clearer interference structures.

Q 26.15 Tue 17:00 Philo 1. OG

X-ray and Electron Emission from peeling Adhesive Tape — Jose L. Mapa[1], •Luka Petersen[1], David Theidel[3], Philip Mosel[1], Charlotte Fischer[1,2], Sven Froehlich[1], Kim-Alessandro Weber[1], Peter Oberta[4,5], Jan-Willem Vahlbruch[2], Hamed Merdji[3], Uwe Morgner[1], and Milutin Kovacev[1] — [1]Leibniz University Hannover, Institute of Quantum Optics, Welfengarten 1, 30167 Hannover, Germany — [2]Leibniz University Hannover, Institute of Radioecology and Radiation Protection, Herrenhäuser Str. 2, 30419 Hannover, Germany — [3]Laboratoire dOptique Appliquée, École nationale supérieure de techniques avancées (ENSTA) ParisTech, CNRS, École polytechnique, 828 Boulevard des Maréchaux, 91120 Palaiseau, France — [4]Rigaku Innovative Technologies Europe s.r.o., Dolní Brežany, 252 41, Czech Republic — [5]Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2, Praha 8, 182 00, Czech Republic

In recent years, several scientific groups have investigated X-ray generation by peeling adhesive tape in vacuum. X-ray generation results from electron emission during the peeling and their interactions with surrounding materials. These studies mainly focused on the tape, system properties, and electron interactions near the detachment point. We examine electron interactions with solid materials along their travel path. We observe a non-homogeneous spatial distribution of electron energies, which we compare with numerical simulations. It shows peeling adhesive tape can serve as a simple, low-cost X-ray source for educational demonstrations and small lab experiments.

Q 26.16 Tue 17:00 Philo 1. OG

Dispersive-Wave Generation in a Kagome-Type Hollow-Core Fibre by Few-Cycle-Pulses — •David Zuber[1,2], Fridolin Jakob Geesmann[1], Ihar Babushkin[1,2,3], and Uwe Morgner[1,2] — [1]Leibniz University Hannover, Institute of Quantum Optics, Hannover, Germany — [2]Cluster of Excellence PhoenixD, Hannover, Germany — [3]Max Born Institute, Berlin, Germany

Tunable ultrashort pulses in the ultraviolet (UV) spectral range have attracted significant attention in a variety of applications, including pump-probe spectroscopy, lithography, and the control of chemical reactions. Conventional laser systems are often limited by the availability of suitable gain media, while their nonlinear counterparts such as optical parametric amplifiers or oscillators face constraints imposed by crystal absorption, phase-matching conditions, and the availability of sufficiently energetic pump photons. The presented UV source is based on dispersive-wave generation in a gas-filled Kagome-type hollow-core fibre. The fibre is pumped with a few-cycle OPCPA system, thereby generating a tunable UV radiation peak accompanied by a broadband background spanning more than 1 PHz. The experimental findings are supported by numerical simulations, which demonstrate the potential for producing few-cycle pulses directly in the UV. In addition, the paper discusses prospects for extending this concept toward the extreme-ultraviolet regime.

Q 26.17 Tue 17:00 Philo 1. OG

Temperature-dependence of two-color laser-induced currents in graphene — •Celina Hüttner[1], Weizhe Li[1], Daniel Lesko[1,2], and Peter Hommelhoff[1,2] — [1]Department Physik, Friedrich-Alexander-Universität (FAU) — [2]Department Physik, Ludwig-Maximilians-Universität München (LMU)

Strong laser fields have previously been used to induce directional currents in solids via symmetry breaking, enabling electronic coherent control on the femtosecond timescale. In graphene, an inversion symmetric semi-metal with extraordinary electronic and optical properties, the photocurrent generation can be controlled by shaping the laser field, for instance through control of the carrier envelope phase or by combining harmonics of a laser pulse. As the latter requires a coherent interaction of both pulses and the electrons in graphene, it enables detailed exploration of decoherence- and dephasing-mechanisms. While the two-color photocurrents have been extensively studied before, the role of phonon-electron scattering remains unclear. In order to investigate this process, we cool graphene to temperatures below 25 K via a continuous flow cryostat setup and measure the two-color photocurrent, at both room and cryogenic temperature. We study the behavior of the photocurrent at different temperatures by varying field strength, polarization and the two-color-phase.

Q 26.18 Tue 17:00 Philo 1. OG

Investigation of the Thermal Behaviour of Yb:YAG and Yb:LuAG in High-Power Bulk Amplifiers — •Julian Siller[1], Arun Paudel[1], Han Rao[1,2], David Zuber[1,2], and Uwe Morgner[1,2] — [1]Leibniz University Hannover, Institute of Quantum Optics, Hannover, Germany — [2]Cluster of Excellence PhoenixD, Hannover, Germany

Ytterbium-doped gain materials are widely used in modern high-power ultrafast laser systems, where thermally induced effects strongly influence beam quality, wavefront stability and hence achievable focusability. While Yb:YAG is a well-established workhorse for solid-state amplifiers, recent studies suggest that Yb:LuAG may exhibit significantly reduced thermo-optical distortions, potentially offering advantages for high power operation. Here, we report on the development of a home-built bulk laser amplifier designed to directly compare the thermal behavior of Yb:YAG and Yb:LuAG under identical pumping conditions. The setup enables controlled high-power pumping in the near-infrared regime and allows for simultaneous measurements of thermal lensing and temperature-dependent gain dynamics. Using beam profiling and M square analysis, we quantify the evolution of thermally induced distortions within each crystal and assess their impact on the amplified output. We expect that the observed differences in the thermo-optical response of the two materials will provide insights into the suitability of Yb:LuAG as a low-distortion alternative to Yb:YAG for next-generation high-power bulk amplifiers.

Q 26.19 Tue 17:00 Philo 1. OG

Characterization of the Temporal Pulse Contrast for Laser-Produced Plasma Applications — •Pia Koopmann, Peer Biesterfeld, Sven Fröhlich, and Milutin Kovacev — Leibniz Universität Hannover - Institut für Quantenoptik, Welfengarten 1, 30167 Hannover, Germany

Ultrafast, high-intensity laser systems are increasingly used to generate secondary radiation sources, such as X-rays and particle beams, offering promising capabilities for scientific and industrial applications. At these intensities, even the comparatively low-intensity laser pedestals and pre-/post-pulses can exceed material ionization thresholds. In particular, the formation of pre-plasma significantly changes the interaction conditions. This can result in effects such as an increased emission of hazardous radiation. Therefore, understanding and controlling these effects is critical for optimizing secondary source performance.

We present the development of an in-house built third-order autocorrelator, designed to characterize the temporal contrast of ultrafast laser systems with high dynamic range. A third-order autocorrelator provides the sensitivity necessary to capture these features and enables systematic studies of how the temporal contrast influences plasma dynamics and the efficiency of Laser-produced plasma sources. The device is optimized to provide the high dynamic range required to resolve weak ns to ps temporal structures, such as pedestals and pre-/post-pulses, which play a decisive role in laser-matter interaction dynamics.