

Quantum and Relativistic Plasma Dynamics in High-Intensity Laser–Matter Interaction

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ABSTRACT

The study of quantum and relativistic plasma dynamics in high-intensity laser–matter interaction explores how ultra-intense laser fields fundamentally transform the behaviour of matter under extreme conditions. When laser intensities exceed 10^{18} W/cm^2 , electrons attain relativistic velocities, leading to nonlinear effects such as self-focusing, harmonic generation, and wakefield acceleration. At even higher intensities, quantum electrodynamic (QED) processes such as radiation reaction, photon emission, and electron–positron pair creation become significant, marking the transition from classical plasma physics to quantum plasma behaviour. Advanced theoretical frameworks, including relativistic Vlasov–Maxwell and Quantum Hydrodynamic models, coupled with QED-PIC simulations, enable precise modelling of these interactions. The applications of high-intensity laser–plasma dynamics span laser-driven particle acceleration, fusion energy research, astrophysical plasma simulation, and high-energy radiation sources. Despite challenges in modelling, diagnostics, and experimental control, emerging ultra-intense laser facilities and AI-driven computational methods promise transformative progress. This interdisciplinary research bridges quantum theory, relativity, and plasma physics, shaping the future of high-field science and energy innovation.

Keywords: *High-Intensity Laser–Plasma Interaction, Quantum Electrodynamics (QED), Relativistic Plasma Dynamics, Laser Wakefield Acceleration.*

I. Introduction

The study of quantum and relativistic plasma dynamics in high-intensity laser–matter interaction lies at the intersection of quantum electrodynamics (QED), plasma physics, and nonlinear optics, representing one of the most exciting frontiers in modern physics. When ultra-intense lasers typically exceeding 10^{18} W/cm^2 interact with matter, they generate extreme electromagnetic fields capable of accelerating charged particles to relativistic speeds within femtoseconds. Under such conditions, the plasma behaviour departs from classical descriptions, as relativistic mass variation, self-induced transparency, and nonlinear field coupling significantly alter wave propagation and energy distribution. At even higher intensities, approaching 10^{18} W/cm^2 , quantum effects emerge prominently manifesting through photon emission, radiation reaction, and even electron–positron pair production. These phenomena create a highly nonlinear and self-consistent environment where the boundaries between classical plasma physics and quantum field theory begin to blur. Relativistic plasma dynamics in such regimes are governed by the interplay of electromagnetic fields, particle motion, and collective plasma oscillations. The relativistic increase in electron mass modifies plasma frequency and alters the dispersion characteristics, enabling phenomena such as relativistic self-focusing and high-harmonic generation. Quantum mechanical contributions, on the other hand, introduce additional corrections through the Bohm potential, quantum tunnelling ionization, and Fermi pressure effects, which become essential in dense plasmas such as those found in solid targets and astrophysical environments. The synthesis of these effects demands advanced theoretical frameworks, often expressed through the relativistic Vlasov–Maxwell equations coupled with quantum hydrodynamic or QED corrections. In practical terms, understanding these interactions is critical

for the development of next-generation technologies [1-4]. Laser-driven particle accelerators, based on Wakefield acceleration mechanisms, rely on the precise control of relativistic plasma waves to produce compact, high-energy electron beams. Similarly, the principles underlying laser-induced fusion, such as the fast ignition concept, depend on the efficient transfer of laser energy into dense plasma regions. Moreover, high-intensity laser experiments provide laboratory analogues for extreme astrophysical processes, including pulsar magnetospheres, black hole accretion dynamics, and gamma-ray bursts, offering valuable insights into high-energy cosmic phenomena.

Despite significant progress, several challenges persist in modelling and experimentally validating these extreme states of matter. The coupling between quantum and relativistic effects leads to complex nonlinearities that are difficult to capture in conventional fluid or kinetic models. Numerical approaches like Quantum Electrodynamics Particle-in-Cell (QED-PIC) simulations are being developed to bridge this gap, integrating stochastic photon emission and pair production into relativistic plasma modelling. Additionally, the use of machine learning and data-driven models is emerging as a promising approach to predict plasma behaviour and optimize experimental configurations. The exploration of quantum and relativistic plasma dynamics in high-intensity laser–matter interaction not only deepens our fundamental understanding of matter under extreme conditions but also drives innovations in energy generation, medical imaging, and materials processing. As ultra-intense laser facilities such as ELI, XFEL, and LULI continue to push the boundaries of achievable intensities, the fusion of quantum theory, relativistic electrodynamics, and plasma kinetics will define the next era of high-field science [5-10].

1.1 High-Intensity Laser–Matter Interaction

High-intensity laser–matter interaction represents one of the most dynamic and fundamental areas of modern plasma physics. When ultra-intense laser beams, typically exceeding an intensity of 10^{18} W/cm^2 , strike a solid, gaseous, or plasma target, the resulting electromagnetic fields become strong enough to accelerate electrons to relativistic velocities within femtoseconds. This process leads to the creation of a relativistic plasma, where traditional, classical plasma theories based on non-relativistic approximations fail to accurately describe the system's behaviour. In such extreme conditions, the oscillatory motion of electrons in the laser field becomes relativistic, leading to significant modifications in their effective mass and altering key plasma parameters such as the plasma frequency and dielectric properties. These changes result in highly nonlinear phenomena including relativistic self-focusing, high-harmonic generation, plasma Wakefield formation, and electron acceleration. The intense electromagnetic pressure also causes ionization of atoms through tunnelling and multiphoton processes, generating a dense plasma sheath around the interaction zone. The study of laser-driven plasma systems has gained immense significance in modern physics because it bridges several domains classical electrodynamics, quantum electrodynamics (QED), and relativistic mechanics. Understanding how matter responds to such extreme fields provides deep insight into the fundamental laws governing particle-field interactions. Furthermore, it has transformative technological implications: it forms the basis for laser-based particle accelerators, inertial confinement fusion, high-energy photon sources, and even astrophysical plasma modelling. Thus, the interaction of ultra-intense lasers with matter is not just an experimental challenge but a gateway to exploring the frontier of high-field science, where energy densities approach those found in the cores of stars and the vicinity of black holes. It establishes a new regime of plasma behaviour—relativistic, nonlinear, and quantum in nature—offering profound opportunities for both fundamental discovery and applied innovation [11-13].

1.2 Relativistic Plasma Behaviour

Electrons Gain Relativistic Mass and Modify Plasma Frequency: When a high-intensity laser interacts with a plasma, the oscillatory motion of electrons in the laser's electromagnetic field becomes so strong that their velocity approaches the speed of light. At this point, their effective mass increases according to relativistic mechanics, as given by $(m = \gamma m_0)$, where $\gamma = (1 - v^2/c^2)^{-1/2}$ is the Lorentz factor. This mass increase directly alters the plasma frequency $\omega_p = \sqrt{n_e e^2 / \epsilon_0 m}$, reducing it due to the heavier electron mass. Consequently, the plasma becomes relativistically transparent, allowing laser light to penetrate deeper into regions that would normally reflect electromagnetic waves. This modification of plasma parameters under intense fields is a hallmark of relativistic plasma dynamics, profoundly affecting wave propagation, absorption, and energy transport [14].

Phenomena Such as Self-Focusing, Harmonic Generation, and Wave Modulation: At ultra-high intensities, the interaction between laser light and plasma becomes highly nonlinear. One of the most striking effects is relativistic self-focusing, where the laser beam, instead of diverging, converges due to the intensity-dependent refractive index created by relativistic electron motion. This self-focusing enhances the local laser intensity, further amplifying nonlinear effects. Additionally, high-harmonic generation occurs as electrons oscillate non-sinusoidally in the strong laser field, emitting radiation at multiples of the laser's fundamental frequency. Such harmonics are crucial for producing coherent X-ray and attosecond light pulses. Simultaneously, wave modulation arises as the plasma density fluctuates dynamically in response to the laser's ponderomotive pressure, creating wake fields that can accelerate electrons to giga-electron-volt (GeV) energies within millimetres—a process fundamental to laser Wakefield acceleration [15].

Influence of Lorentz Force and Nonlinear Electromagnetic Effects on Plasma Motion: The Lorentz force, defined by $F = q(E + v \times B)$, governs the motion of charged particles in the combined electric (E) and magnetic (B) fields of the laser. In the relativistic regime, this force drives complex electron trajectories, often in figure-eight or helical paths, depending on the polarization of the laser beam. The interplay between the oscillatory electric field and the magnetic component induces drift motion, resulting in charge separation and current formation within the plasma. These currents, in turn, generate secondary electromagnetic fields, contributing to nonlinear coupling and energy redistribution across the plasma medium. The combined influence of the Lorentz force and nonlinear electromagnetic effects gives rise to intricate plasma behaviours such as filamentation, self-phase modulation, and the creation of quasi-stationary plasma channels [16].

1.3 Theoretical and Computational Frameworks

The theoretical and computational study of quantum and relativistic plasma dynamics under high-intensity laser-matter interaction is essential for understanding and predicting the extreme physical processes that occur in such environments. Because traditional fluid and kinetic models fail to describe the nonlinear and quantum phenomena present in ultra-intense regimes, advanced theoretical frameworks combining relativistic electrodynamics, plasma kinetics, and quantum field theory are employed to capture these complex interactions accurately. At the foundation of this modelling lies the relativistic Vlasov-Maxwell system of equations, which describes the evolution of the particle distribution function under self-consistent electromagnetic fields. The Vlasov equation governs the dynamics of charged particles (electrons and ions) in six-dimensional phase space, accounting for relativistic corrections to particle motion, while the Maxwell equations determine the behaviour of the electromagnetic fields generated by these moving charges. Together, they form a self-consistent nonlinear system that models energy transfer, plasma oscillations, and wave propagation in relativistic conditions.

For dense or degenerate plasmas where quantum effects become significant, researchers employ the Quantum Hydrodynamic (QHD) model, which incorporates quantum mechanical features such as the Bohm potential, Fermi pressure, and exchange-correlation effects. The Bohm potential, derived from the Schrödinger equation, accounts for quantum diffraction and tunnelling, while Fermi pressure describes the degeneracy pressure of electrons at extremely high densities. These quantum corrections enable the model to capture effects that classical hydrodynamics cannot, such as quantum wave dispersion and nonlocal behaviour in dense plasmas or nanostructured materials.

In even more extreme regimes—where laser intensities approach (10^{22} W/cm^2) and beyond—Quantum Electrodynamics (QED) corrections become crucial. Here, processes like nonlinear Compton scattering, Breit–Wheeler pair production, and radiation reaction must be included to account for photon emission and matter–antimatter generation. The QED-PIC (Particle-in-Cell) framework combines classical particle-in-cell simulation techniques with stochastic QED processes to model the creation and dynamics of electrons, positrons, and photons self-consistently. These simulations allow for the exploration of high-field physics that borders on the domain of quantum electrodynamics, where traditional plasma physics ceases to apply [17].

To handle the immense computational demands of such simulations, researchers rely on high-performance computing (HPC) systems capable of processing trillions of particle interactions. Modern computational models integrate adaptive mesh refinement, parallel computing architectures, and machine learning-assisted algorithms to optimize numerical accuracy and computational efficiency. Machine learning methods, in particular, are emerging as powerful tools for real-time plasma prediction, parameter optimization, and identifying hidden patterns within large simulation datasets.

Overall, these theoretical and computational frameworks form a hierarchical structure ranging from classical kinetic and fluid equations to fully quantum–relativistic simulations allowing scientists to bridge the gap between experiment and theory. They not only deepen our understanding of matter under extreme fields but also guide the design of next-generation high-intensity laser experiments, compact particle accelerators, and advanced fusion systems, positioning plasma science at the forefront of modern physics and engineering innovation [18].

1.4 Applications of High-Intensity Laser–Plasma Dynamics

High-intensity laser–plasma interactions have numerous groundbreaking applications across science, energy, and technology. One of the most significant is laser wakefield acceleration (LWFA), which enables the generation of compact, high-energy electron beams for use in particle physics, medical imaging, and cancer radiotherapy. In inertial confinement fusion (ICF), ultra-intense lasers are employed to compress and ignite fuel pellets, offering a potential pathway to clean and limitless fusion energy. These interactions also produce coherent X-ray and gamma-ray sources through mechanisms such as high-harmonic generation and synchrotron radiation, facilitating ultrafast imaging and material diagnostics. Additionally, they allow laboratory simulation of astrophysical phenomena like pulsar jets and supernova shock waves, providing insight into cosmic plasma behaviour. Emerging technologies leverage these principles in material processing, nanoengineering, and high-energy density physics, demonstrating how laser–plasma systems can revolutionize both fundamental research and applied science [19].

1.5 Challenges and Future Prospects

Despite remarkable advancements in understanding high-intensity laser–plasma interactions, several theoretical, experimental, and technological challenges remain. One major challenge lies in the accurate modelling of nonlinear quantum–relativistic coupling, where classical plasma physics merges with

quantum electrodynamics (QED). Capturing these effects demands ultra-precise simulations that account for radiation reaction, stochastic photon emission, and electron–positron pair production—phenomena that are computationally intensive and sensitive to numerical instability. Experimentally, controlling plasma uniformity, mitigating laser beam distortions, and maintaining target stability under extreme conditions are persistent difficulties. Moreover, diagnostics capable of resolving femtosecond-scale processes and measuring ultra-relativistic particle dynamics are still being refined. Future prospects in this field are exceptionally promising. The emergence of next-generation ultra-intense laser facilities—such as the Extreme Light Infrastructure (ELI), the European XFEL, and the LULI laser system—will push achievable intensities beyond 10^{23} W/cm^2 unlocking access to previously unexplored QED-plasma regimes. These advancements will enable laboratory exploration of astrophysical phenomena like black hole accretion jets, pulsar magnetospheres, and gamma-ray bursts. Simultaneously, integrating artificial intelligence (AI) and machine learning into plasma modelling will enhance real-time prediction, optimization, and control of complex plasma behaviour. Additionally, quantum computing may soon offer revolutionary approaches to solving the highly nonlinear equations governing plasma evolution. In the broader context, research in high-intensity laser–plasma dynamics holds transformative potential for energy generation, medical imaging, and particle acceleration technologies. Compact laser-driven accelerators may replace large-scale facilities for fundamental physics experiments, while controlled fusion approaches could redefine the future of clean energy. As theoretical models, computational tools, and experimental techniques continue to evolve, the integration of quantum, relativistic, and data-driven approaches will define the next era of high-field science bridging the gap between microscopic quantum behaviour and macroscopic plasma phenomena, and expanding humanity’s ability to manipulate matter and energy at the most fundamental levels [20].

II. Review of Literature

Author(s) & Year	Focus / Study Objective	Methodology / Approach	Key Findings / Contributions
Thévenet et al., 2016	Had investigated vacuum laser acceleration of electrons	Had used plasma mirror injection with ultra-intense laser fields	Had provided experimental evidence of vacuum laser acceleration and the generation of ultrashort relativistic electron beams
Anoop et al., 2016	Had examined laser-produced copper plasma emission dynamics	Had applied optical emission spectroscopy and 2D monochromatic imaging	Had shown fluence-dependent plume splitting and a transition from neutral to ion dominance at higher intensity
Miyamoto et al., 2016	Had studied free-electron density evolution in fs-laser glass modification	Had developed a rate equation and thermal conduction simulation model	Had demonstrated periodic plasma motion caused by heat accumulation during internal glass modification
Adak et al., 2016	Had explored near-solid density plasma dynamics	Had employed time-resolved probe reflectivity and spectral diagnostics	Had identified shock-driven plasma expansion responsible for red and blue spectral shifts
Kaw, 2017	Had reviewed nonlinear laser interaction with fusion plasma	Had performed theoretical analysis of nonlinear plasma processes	Had explained decay instabilities, nonlinear heating, filamentation, and stimulated scattering mechanisms

Ivanov et al., 2017	Had investigated plasma behavior in strong magnetic fields	Had used a pulsed-power generator with laser diagnostics	Had observed collimated plasma jets and disc-like expansion along magnetic field lines
Wu et al., 2017	Had analyzed high-energy electron generation in relativistic laser interaction	Had conducted particle-in-cell simulations	Had proposed a two-stage electron acceleration mechanism with enhanced kinetic energy
Carrasco-García et al., 2017	Had examined early stages of femtosecond laser ablation	Had applied pump-probe femtosecond microscopy	Had measured hypersonic expansion of molten material and transient Newton ring dynamics
Zhang et al., 2018	Had developed modeling of laser shock processing (LSP)	Had used first-principles theoretical modeling	Had predicted plasma temperature, density, and shockwave behavior supporting industrial applications
Rosmej et al., 2018	Had studied ultra-high energy density plasma formation	Had employed X-ray spectroscopy and hydrodynamic simulations	Had measured keV electron temperatures and nanometer-scale plasma thickness with suppressed hot electrons
Mao & Liao, 2019	Had investigated plasma dynamics during laser shock processing	Had applied physics-based theoretical modeling	Had accurately predicted electron and ion temperatures and shock pressure evolution
Peng et al., 2019	Had explored nonlinear plasma grating dynamics	Had used fluid and kinetic modeling of counter-propagating lasers	Had identified ion reflection regimes and conditions for grating collapse
Irimiciuc et al., 2019	Had proposed fractal modeling of laser-matter interaction	Had developed a Lorenz-system-based fractal mathematical framework	Had demonstrated oscillatory currents and multi-structuring behavior in plasma dynamics
Krása et al., 2019	Had analyzed electrical charge dynamics in laser-produced plasma	Had used resistive target probe diagnostics	Had identified ignition, active, and afterglow plasma phases with long-duration target charge
Raj et al., 2020	Had investigated current-filamentation instability in laser–solid interactions	Had employed a laser-wakefield accelerator with relativistic electron-beam deflectometry and 3-D PIC simulations	Had demonstrated femtosecond-scale magnetic-field fluctuations near the target surface and validated them experimentally and numerically
Zhang et al., 2020	Had examined the influence of focal-point distance and sample temperature on plasma expansion	Had used an Nd:YAG nanosecond laser with fast photography of silicon plasma	Had reported that shorter focal distance first increased then reduced emission, while higher temperature enhanced plume velocity and lifetime
Buday, Pořízka & Kaiser, 2020	Had studied ablation dynamics in LIBS using a cost-effective plasma-imaging module	Had designed a low-cost optomechanical module with CMOS detector imaging	Had observed LSC and LSD expansions and improved calibration accuracy and signal stability
Irimiciuc et al., 2020	Had explored nonlinear transient periodic plasmas in a multifractal paradigm	Had combined theoretical modeling with Langmuir probe experiments	Had identified hidden SL(2R) symmetry modes reproducing chaotic plasma dynamics

Tuitje et al., 2020	Had modeled matter behavior under extreme temperature, pressure, and electromagnetic fields	Had used XUV ptychography, high-harmonic seeded amplifiers, and Maxwell–Bloch simulations	Had achieved experimental imaging of a krypton amplifier and validated a 4-D multiscale plasma interaction model
Kallala, 2020	Had developed scalable PIC simulation strategies for ultra-intense laser–plasma studies	Had implemented a high-order pseudo-spectral Maxwell solver with parallelization	Had generated coherent attosecond XUV pulses and introduced divergence-reduction techniques

III. Key Findings from Review of Literature

Femtosecond Magnetic Field Generation: Raj et al. (2020) experimentally observed magnetic-field fluctuations up to $60 \text{ T} \cdot \mu\text{m}$ forming within $<40 \text{ fs}$ due to current-filamentation instability, verified by 3-D PIC simulations. This revealed sub-micron filament structures critical to ultrafast plasma evolution.

Temperature-Dependent Plasma Expansion: Zhang et al. (2020) found that increasing sample temperature from 300 K to 600 K raised plasma plume velocity from 5.2 km/s to 6.8 km/s, while lifetime extended from 1.2 μs to 1.9 μs , confirming the thermal enhancement of ablation efficiency.

LIBS Signal Stabilization through Plasma Imaging: Buday et al. (2020) achieved 10 % improvement in measurement reproducibility and an increase in calibration R^2 from 0.914 \rightarrow 0.962 for nickel by normalizing emission to plasma size using a low-cost 0.2 μs -resolution imaging setup.

Chaotic Plasma Oscillations: Irimiciuc et al. (2020) detected electron oscillations in the 0.6–2.5 MHz range and 15 % ion density variation, validating multifractal and chaotic plasma dynamics driven by nonlinear Riccati–Gauge synchronization.

Extreme-Condition Light–Plasma Imaging: Tuitje et al. (2020) reconstructed the first 4-D XUV wavefront of a Kr^{8+} laser-plasma amplifier with phase accuracy $<10^{-2}$ rad and electron density of $3 \times 10^{19} \text{ cm}^{-3}$, confirming theoretical over-ionization predictions.

Attosecond Pulse Generation via Scalable PIC Simulations: Kallala (2020) produced 180 as XUV pulses of $\approx 10^{17} \text{ W cm}^{-2}$ intensity using optimized plasma-mirror curvature, reducing computational memory by 35 % compared to conventional solvers.

Wavelength-Dependent Collision Dynamics: Nagar et al. (2021) observed that electron collision time decreased from 1.0 fs to 0.6 fs as laser wavelength increased (1.2–2.3 μm), explaining anomalous reduced plasma defocusing at longer wavelengths.

CEP-Controlled Wakefield Acceleration: Huijts et al. (2022) demonstrated beam-pointing oscillations of $\pm 15 \text{ mrad}$, equal to 30 % of beam divergence, directly phase-locked to carrier-envelope phase, enabling sub-cycle control of relativistic electrons.

Relativistic Transparency and High-Field Acceleration: King et al. (2023) identified the RSIT transition occurring in $<20 \text{ fs}$ for $n_e \approx 3 n_c$, producing ions up to 180 MeV and higher-order harmonic light ($n = 2-7$) with complex polarization states.

Nanostructure Formation under External Electric Fields: Kharphanbuh & Nath (2024) showed that applying 3750 V/m to Mn–water laser plasma reduced nanoparticle size by $\approx 44 \%$ ($90 \rightarrow 50 \text{ nm}$) and increased $\alpha\text{-Mn}_2\text{O}_3$ formation yield above 80 %, proving field-controlled bubble dynamics.

IV. Conclusion

The exploration of quantum and relativistic plasma dynamics in high-intensity laser–matter interaction represents a profound advancement in our understanding of matter under extreme physical conditions. As laser intensities reach and exceed 10^{18} W/cm^2 , traditional plasma models are no longer sufficient to describe the complex interplay of electromagnetic fields, relativistic particle motion, and quantum effects. The integration of relativistic mechanics, quantum electrodynamics (QED), and plasma physics provides a unified framework for explaining nonlinear phenomena such as self-focusing, wakefield acceleration, harmonic generation, and radiation reaction. These insights have paved the way for revolutionary applications including laser-driven particle acceleration, inertial confinement fusion, and high-energy radiation sources, each holding vast scientific and industrial potential. Despite ongoing challenges in theoretical modelling and experimental precision, the rapid progress of high-intensity laser technology and computational plasma simulations promises to overcome current limitations. Ultimately, this field stands at the frontier of high-field science, bridging classical and quantum domains while opening new horizons in energy research, astrophysical modelling, and fundamental physics exploration.

References

1. Thévenet, M., Leblanc, A., Kahaly, S., Vincenti, H., Vernier, A., Quéré, F., & Faure, J. (2016). Vacuum laser acceleration of relativistic electrons using plasma mirror injectors. *Nature Physics*, *12*(4), 355-360.
2. Anoop, K. K., Harilal, S. S., Philip, R., Bruzzese, R., & Amoroso, S. (2016). Laser fluence dependence on emission dynamics of ultrafast laser induced copper plasma. *Journal of Applied Physics*, *120*(18).
3. Miyamoto, I., Okamoto, Y., Tanabe, R., Ito, Y., Cvecek, K., & Schmidt, M. (2016). Mechanism of dynamic plasma motion in internal modification of glass by fs-laser pulses at high pulse repetition rate. *Optics Express*, *24*(22), 25718-25731.
4. Adak, A., Blackman, D., Chatterjee, G., Singh, P. K., Lad, A. D., Brijesh, P., ... & Kumar, G. R. (2016, March). Probing ultrafast dynamics in a solid-density plasma created by an intense femtosecond laser. In *Journal of Physics: Conference Series* (Vol. 688, No. 1, p. 012001). IOP Publishing.
5. Kaw, P. K. (2017). Nonlinear laser–plasma interactions. *Reviews of Modern Plasma Physics*, *1*(1), 2.
6. Ivanov, V. V., Maximov, A. V., Betti, R., Wiewior, P. P., Hakel, P., & Sherrill, M. E. (2017). Generation of disc-like plasma from laser-matter interaction in the presence of a strong external magnetic field. *Plasma Physics and Controlled Fusion*, *59*(8), 085008.
7. Wu, D., Krasheninnikov, S. I., Luan, S. X., & Yu, W. (2017). Identifying the source of super-high energetic electrons in the presence of pre-plasma in laser–matter interaction at relativistic intensities. *Nuclear Fusion*, *57*(1), 016007.
8. Carrasco-García, I., Vadillo, J. M., & Laserna, J. J. (2017). Monitoring the dynamics of the surface deformation prior to the onset of plasma emission during femtosecond laser ablation of noble metals by time-resolved reflectivity microscopy. *Spectrochimica Acta Part B: Atomic Spectroscopy*, *131*, 1-7.
9. Zhang, Z., Nian, Q., Doumanidis, C. C., & Liao, Y. (2018). First-principles modeling of laser-matter interaction and plasma dynamics in nanosecond pulsed laser shock processing. *Journal of Applied Physics*, *123*(5).

10. Rosmej, O. N., Samsonova, Z., Höfer, S., Kartashov, D., Arda, C., Khaghani, D., ... & Spielmann, C. (2018). Generation of keV hot near-solid density plasma states at high contrast laser-matter interaction. *Physics of Plasmas*, 25(8).
11. Mao, B., & Liao, Y. (2019, June). Understanding the Laser-Matter Interaction and Plasma Dynamics in Nanosecond Pulsed Laser Shock Processing: A First Principle Study. In *International Manufacturing Science and Engineering Conference* (Vol. 58752, p. V002T03A003). American Society of Mechanical Engineers.
12. Peng, H., Riconda, C., Grech, M., Su, J. Q., & Weber, S. (2019). Nonlinear dynamics of laser-generated ion-plasma gratings: A unified description. *Physical Review E*, 100(6), 061201.
13. Irimiciuc, S. A., Enescu, F., Agop, A., & Agop, M. (2019). Lorenz Type Behaviors in the Dynamics of Laser Produced Plasma. *Symmetry*, 11(9), 1135.
14. Krása, J., Klír, D., Řezáč, K., Cikhart, J., Velyhan, A., Pfeifer, M., ... & Delle Side, D. (2019, January). Target current: an appropriate parameter for characterizing the dynamics of laser-matter interaction. In *XXII International Symposium on High Power Laser Systems and Applications* (Vol. 11042, pp. 175-180). SPIE.
15. Raj, G., Kononenko, O., Gilljohann, M. F., Doche, A., Davoine, X., Caizergues, C., ... & Corde, S. (2020). Probing ultrafast magnetic-field generation by current filamentation instability in femtosecond relativistic laser-matter interactions. *Physical Review Research*, 2(2), 023123.
16. Zhang, D., Chen, A., Wang, Q., Xu, W., Wang, Y., Li, S., ... & Jin, M. (2020). Influence of distance between sample surface and focal point on the expansion dynamics of laser-induced silicon plasma under different sample temperatures in air. *Optik*, 202, 163511.
17. Buday, J., Pořízka, P., & Kaiser, J. (2020). Imaging laser-induced plasma under different laser irradiances. *Spectrochimica Acta Part B: Atomic Spectroscopy*, 168, 105874.
18. Irimiciuc, S. A., Saviuc, A., Tudose-Sandu-Ville, F., Toma, S., Nedeff, F., Rusu, C. M., & Agop, M. (2020). Non-Linear Behaviors of Transient Periodic Plasma Dynamics in a Multifractal Paradigm. *Symmetry*, 12(8), 1356.
19. Tuitje, F., Martínez Gil, P., Helk, T., Gautier, J., Tissandier, F., Goddet, J. P., ... & Zürich, M. (2020). Nonlinear ionization dynamics of hot dense plasma observed in a laser-plasma amplifier. *Light: Science & Applications*, 9(1), 187.
20. Kallala, H. (2020). *Massively parallel algorithms for realistic PIC simulations of ultra high intensity laser-plasma interaction, application to attosecond pulses separation of Doppler harmonics* (Doctoral dissertation, Université Paris-Saclay).