Coherent Radiation from Ultrashort Intense Laser Driven Solid Density Matter

PhD Thesis Booklet

Mojtaba Shirozhan

Supervisor:

Subhendu Kahaly, PhD

ELI-ALPS, Wolfgang Sandner utca 3, H-6728 Szeged, Hungary

Doctoral School of Physics

Institute of Physics

University of Szeged

Faculty of Science and Informatics

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Introduction and Motivation

Recent advances in ultrashort laser physics have enabled access to peak powers at Petawatt levels in various facilities already existing [1] or being built around the world (like Extreme Light Infrastructure-Attosecond Light Pulse Source (ELI-ALPS) facility [2, 3]). Such lasers when focused spatio-temporally to spot sizes few μm wide and pulse durations several femtosecond brief on a solid density target, can deliver peak intensities high enough to instantly ionize the matter in its rising edge. The peak of the pulse then interacts with the produced plasma inducing relativistic charge dynamics. Such interactions significantly alter both the driving electromagnetic field and the driven system, the underlying physics of which encapsulates multidisciplinary topics of interest from fundamental and applied research point of view. State of the art lasers has been able to reach focused peak intensities in excess of $\sim 10^{21}$W/cm^2 within sub-two cycles [4], and peak intensities of $\sim 10^{23}$W/cm^2 [5] in the multi-cycle domain, opening up further new possibilities in ultra high intensity laser plasma science.

In such an interaction, the fast and collective response of the plasma constituents to externally imposed intense electromagnetic fields allows for the readjustment of the particle distributions and subsequently the internally-driven electric and magnetic fields. This type of plasma dynamics holds key to several applications in different fields of science and technology, like flash radiobiology [6], laser driven particle accelerators [7], laboratory astrophysics [8, 9], generation of intense coherent extreme ultraviolet (EUV or XUV) pulses through high order harmonics from plasma surfaces [10], relativistic electrodynamics [11, 12], plasma-based light amplifiers [13], plasma focusing lens at extreme intensity [14] among countless others. An intrinsic aspect of intense laser-matter interaction is the reflection of ultrashort pulses from such strongly driven solid density systems. This phenomenon underpins a range of frontier applications, including laser-driven acceleration of electron bunches [15, 16] and the generation of intense XUV radiation via high-order harmonic generation (HHG) from plasma surfaces [10, 17, 18] among others.

The unique capabilities of laser–plasma-based sources to produce ultrashort XUV pulses, emanating from such a reflection process, have sparked considerable interest, owing to their potential for probing matter with unprecedented temporal and spatial resolution. In particular, surface high harmonic generation (SHHG)—arising from the interaction of relativistic laser pulses with solid-density targets—has been shown both numerically and experimentally to yield XUV beams with significantly enhanced photon flux compared to gas-phase HHG systems [18–21]. These advances position SHHG as a promising route toward compact, high-brightness attosecond light sources for ultrafast science.

Despite the growing body of research and the paramount interest of the topic, the reflection dynamics in relativistic plasma systems remains relatively unexplored and is still far from being well understood. The complexity partially stems from the highly nonlinear and transient nature of the interaction, where relativistic electron motion, plasma instabilities, and field-induced surface deformation all play interdependent roles: all of which make the simplistic modeling less favorable. In addition, the technological demands of designing controlled, reproducible experimental conditions at such extreme intensities pose substantial challenges. This significantly limits the number of state-of-the-art advanced platforms that are capable of probing these phenomena in a well-controlled manner, restricting the available experimental landscape.

This dissertation is motivated by the need to bridge these gaps through a systematic investigation of the underlying physical mechanisms governing relativistic reflection and its role in XUV generation as well as by advancing experimental strategies for probing signatures of such reflection, through SHHG. By undertaking both theoretical modeling and numerical computations, the aim is to deepen the understanding of SHHG processes. These insights are crucial for guiding the development of next generation relativistic plasma mirror platforms capable of supporting high-repetition-rate, high-flux attosecond sources as well as for interpreting results obtained from the SHHG experiments performed in the framework of the SHHG-SYLOS beamline at ELI-ALPS [22, 23].

Objectives of the Thesis

This doctoral thesis seeks to address key gaps in our understanding of the complex and interrelated physics governing light–matter interactions, with the goal of optimizing XUV pulse generation from relativistic plasmas. The research focuses on the intersection of special relativity, plasma physics, and electrodynamics, where nonlinear dynamics and extreme field conditions converge to shape high-harmonic emission processes.

A major goal of the research is to attain deep insights on coherently driven relativistic sub-cycle laser-plasma interactions, that underpin a wide array of high field applications, from particle acceleration to attosecond pulse generation. By exploring these interactions, this work enables indication, prediction and/or identification of new domains of potential operation.

To achieve this, the thesis adopts a multi-pronged approach that integrates semi-analytical modeling, Particle-In-Cell (PIC) simulations, and experimental investigations of SHHG. This comprehensive approach is designed to address a hierarchy of physical processes with increasing complexity, and is closely aligned with the implementation of the Surface Plasma Attosource Beamline at ELI-ALPS—a facility dedicated to producing intense attosecond XUV pulses [22–24].

A central objective is to investigate the nonlinear dynamics of relativistic electrons at plasma surfaces and their role in shaping the spectral and temporal characteristics of the emitted XUV radiation. Due to the inherently nonlinear dynamics of relativistic electrons, the characteristics of the emitted XUV radiation are highly sensitive to the interaction conditions. This PhD thesis aims to investigate the relevant physical mechanisms governing this process and to identify the laser and plasma parameters that optimize the energy conversion efficiency in generation of coherent XUV radiation. The computational findings of the thesis, on one hand, have directly informed the design of the optimal interaction configuration of the SHHG SYLOS beamline developed and implemented at ELI-ALPS. On the other hand, this foundation had the objective to successfully provide a robust framework for interpreting the results of the experiments performed in the SHHG-SYLOS beamline. Ultimately, the research contributes to the development of next generation plasma mirror platforms and high-repetition-rate attosecond sources, advancing both fundamental science and applied photonics.

Methodology

The first theoretical treatment of light reflection from relativistic moving mirrors was proposed in the seminal work in 1905 by Albert Einstein [25]. Since then it continues to be a topic of significant interest in modern relativistic optics [26] which demands a comprehensive approach combining (i) analytical modeling with (ii) numerical simulations and (iii) state-of-the-art experiments. The solutions to the problem of this research will involve a step-wise approach, beginning with the physics of relativistic reflections of the light from the moving plasma surfaces. Due to the complexity of the problem, the numerical methods such as PIC simulation is employed to optimize and predict the outcomes of interactions observed in the real experiments.

The dissertation begins with an overview of the theoretical framework and essential mathematical relations describing the fundamental physical concepts of the relativistic interaction of laser and plasma (Chapter 2). These governing principles covers the key parameters of the laser-plasma interaction in the high field physics, including the single electron picture in the inhomogeneous electromagnetic (EM) fields, the quivering motions of the electrons as well as their net longitudinal drift due to the produced time-averaged force (ponderomotive force) and the dynamics of the plasma medium produced due to the ionization of the target material, irradiated by the high irradiance incident laser pulse. Owing to the relativistic nature of such interactions, leading to the generation of frequency upshifted radiations via reflection of the near infrared laser pulse off the relativistically moving ob-

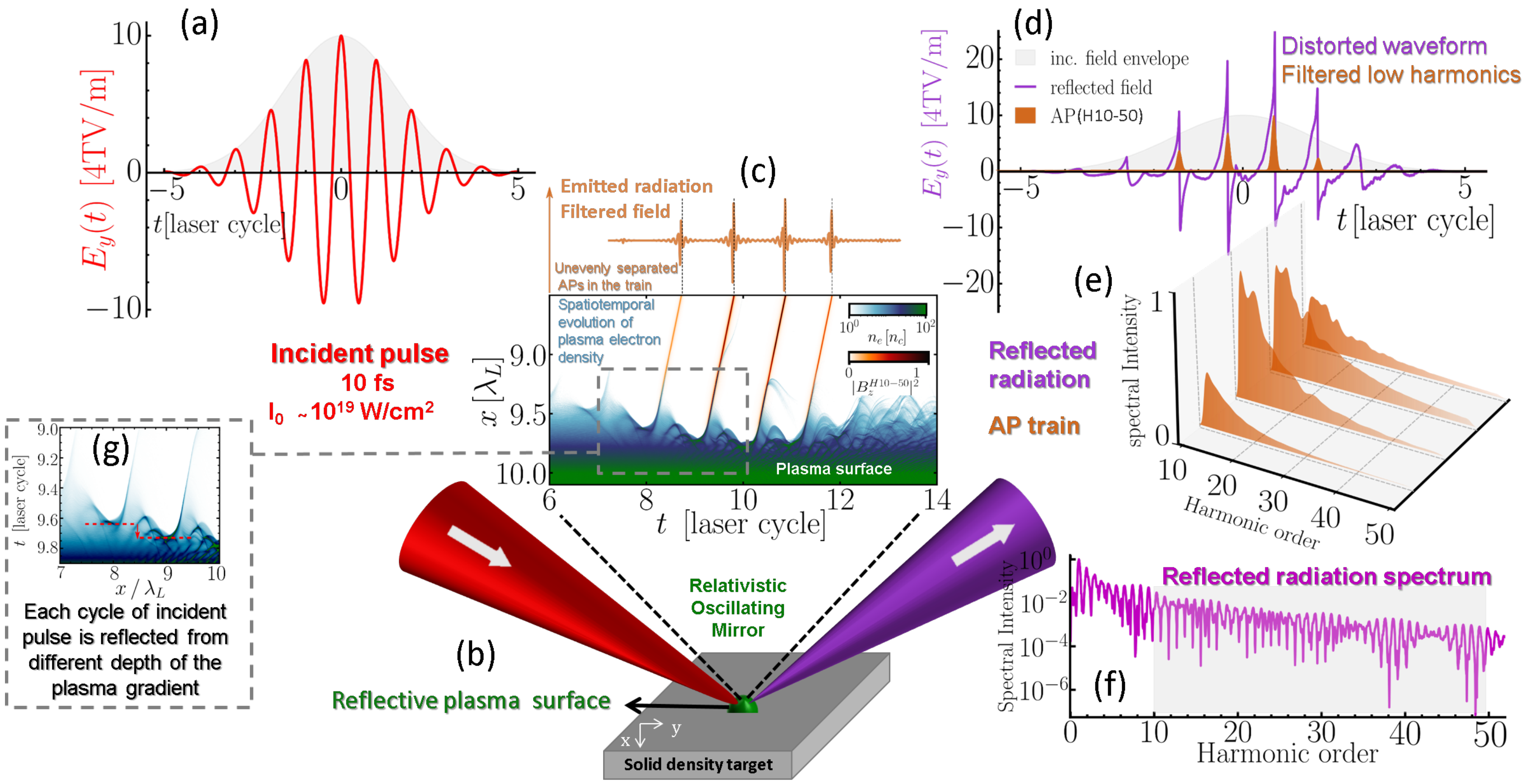

Figure 1: *schematic drawing of the HHG from surface of the solid density target. An ultra-intense laser pulse (a) impinges the solid density target and ionizes the interaction point on the surface (b), whose density reaches above the critical electron density n_c. This results in the formation of a reflective surface which oscillates periodically. Due to the interaction of nearly each cycle of the incident pulse with the solid density target, the surface electrons are driven to perform a push-pull movement (c), which leads to the emission of sub-cycle pulses in asec time scale (d). The interference of in-phase sub-cycle pulses (e) results in the generation of high harmonics in the reflected radiation spectrum (f). The integrated spectrum of the reflected radiation is filtered out to contain harmonics 10 to 50. The spatio-temporal evolution of the surface electrons during interaction (in green-blue colorbar) implies that each cycle of the incident pulse is reflected at different depth of the plasma gradient (g), which might lead to the generation of unevenly separated APs in the train.* ($\lambda_L = 800$ *nm*, $T_L = 2.7$ *fs*)

jects, the physics of relativistic motions under various conditions, in the context of special theory of relativity is studied.

Particle-in-Cell simulation is a cornerstone computational technique in relativistic plasma physics, enabling self-consistent modeling of charged particle dynamics and EM fields in extreme regimes. For a major part of the work performed under this dissertation, I perform virtual experiments via high performance computer simulations, based on PIC approach, in order to mimic as close as possible the real experimental scenario. To apply fundamental physical laws and simulate phenomena provide an effective means for realizing, predicting, and optimizing interaction outcomes, while also revealing critical microscopic insights into the complex processes involved.

The PIC simulation method contemplates the interplay between EM fields and charged particles (as the constituents of a plasma medium) on a spatial grid. In this method due to the collective behavior of the plasma particles, they can be replicated in a big ensemble of particles, i.e. *macroparticle*. Each individual macroparticle represents a huge number of physical particles of same species (e.g. macro-electrons and macro-ions) and since they have the same charge-to-mass ratio, they follow the same trajectory when they are under the influence of an external EM fields [27]. The kinetic theory of particles describes temporal evolution of the plasma via a particle distribution function in the phase space $(\vec{r}, \vec{p})$ at a given time as $f(\vec{r}, \vec{p}, t)$. In the classical picture of a collisionless plasma, the Maxwell's equations and Newton-Lorentz equation of motion determine the behavior of plasma particles in the presence of the fields. These equations are solved for each macroparticle (electron and ion) once per time step. The contribution of macroparticles to the charge and current densities ρ and $\vec{J}$ allows to solve the Maxwell's equation on the grid points. The PIC methods follows a four-step procedure to evolve the macroparticles under the action of EM fields in a self-consistent manner. First the position and velocity of macroparticles are deposited on the grid points to obtain the charge and current densities. Then, using these sources, the Maxwell's equations are solved to calculate the value of EM fields on each grid. After that, the value of Lorentz force is interpolated at the location of each macroparticles. Finally, solving the equation of motion for these particles gives rise their updated position and velocity. Such algorithm is iterated during each time step. By utilizing the PIC simulation, I aimed to identify the optimal interaction conditions for a wide range of laser and plasma parameters, which are accessible in the real SHHG experiment at ELI-ALPS. In this series of simulations, the various interaction parameters, including peak intensity ($a_0 = 0.1 - 6$), angle of incidence ($\theta_I = 0 - 60$), and polarization of the driving pulse on different plasma targets are studied.

In this PhD thesis, two distinct approaches of generating coherent XUV radiation (ranging from $\simeq 120$nm to 10nm) are followed. In the first scheme (described thoroughly in chapter 3 of the main text), which is based on the coherent Thomson back-scattering of the laser pulse off a relativistically driven electron layer [28], a single attosecond pulse (AP) can be produced with a narrow bandwidth spectrum peaked at the XUV range of the EM spectrum. An intense drive laser pulse irradiates normally a nanometer foil target in the blown-out regime of interaction, separating and accelerating the plasma electrons to relativistic velocities. Then, a counter-propagating main pulse with cross-polarization interacts with such relativistic and reflective structure and gets partially reflected. As the result of this *single relativistic reflection*, and depending on the velocity of the relativistic mirror, the reflected radiation experiences an upshift in its frequency components, enabling the generation of a single pulse in the attosecond (asec) time scale.

In the second approach, where an intense pulse is incident obliquely on a semi-infinite overdense plasma target, i.e. Plasma Mirror (PM), the driven collective dynamics of the electrons at the vacuum-plasma interface emits a burst of short wavelength APs. This is due to the periodic Doppler upshifting of the driving laser pulse, reflected from the overdense plasma interface, which oscillates relativistically with the frequency of the incident pulse field. Such ultra-fast response of the plasma electrons located within the skin depth of plasma surface to the EM fields of the driving laser, modulates the energy distribution of the reflected pulse (in amplitude and phase) [29–31]. In this context (detailed in chapter 4 of the thesis), the generation of the high efficiency XUV pulse is tied to the finely controlled and adjusted interaction conditions. In order to gain a concise overview of the interaction of ultra-intense laser pulses with overdense plasma and its *multiple relativistic reflections* from the PM, the simulation results obtained from the 1D3V PIC code are depicted in Figure 1. An ultra-intense laser pulse (a) impinges the solid density target and ionizes the interaction point on the surface (b), whose density reaches above the critical electron density n_c. This results in the formation of a reflective surface, which oscillates periodically during the interaction. Due to the interaction of each cycle of the incident pulse (red) with the solid density target, the surface electrons are driven to perform a push-pull movement (c). As such surface electrons are accelerated toward vacuum, they form an overdense electron bunch with relativistic velocity, which can potentially reflect the incoming pulse and induce Doppler frequency upshift in the the reflected beam. This leads to the emission of sub-cycle pulses in asec time scale (d). The interference of in-phase sub-cycle pulses (e) results in the generation of high harmonics in the reflected radiation spectrum (f). The spectral interference of APs is manifested in the generation of the harmonics of fundamental frequency in the broad modulated spectrum of the reflected radiation. The experimental results for the generation of XUV radiations presented in the framework of this thesis are based on this principle through the relativistic interaction of laser and solid density plasmas.

A central achievement of this thesis is the implementation and experimental realization of the SHHG-SYLOS beamline, designed to demonstrate a relativistic plasma mirror capable of meeting all critical conditions for efficient and stable SHHG. The beamline design was guided by extensive numerical simulations, ensuring optimal interaction geometry and plasma conditions. To drive the plasma mirror, we employed the state-of-the-art SYLOS laser system, delivering few-cycle, broadband pulses under tight focusing conditions. This configuration enables peak intensities exceeding 10^{19} W/cm^2 on target, essential for entering the relativistic regime.

To support high-repetition-rate operation—ranging from > 10 Hz up to 1 kHz—we developed a novel, continuously operating, free-flowing liquid plasma mirror target. This system maintains the required vacuum conditions while providing a replenishable surface for each laser shot. Achieving high temporal contrast in the laser pulse was critical for controlling the spatial profile of the plasma and minimizing pre-pulse effects that could degrade mirror quality. In addition a pump-probe scheme has been implemented to optimally control the relativistic plasma mirror efficiency for SHHG. Importantly, the use of few-cycle pulses enables the possibility of temporal gating of the HHG process, allowing for the generation of isolated attosecond bursts in near future. In the SHHG experiments presented in this thesis, the SYLOS-3 laser system with up to 110 mJ pulses have been employed to irradiate the liquid leaf target, initiating relativistic collective electron dynamics at the plasma surface. This interaction leads to the emission of intense XUV radiation. The high repetition rate and stability of the system offer a significant advantage for data acquisition, facilitating detailed studies of ultrafast phenomena with improved statistical reliability.

Summary of the new results:

Point I.

Relativistic SHHG stems from Doppler upshifted, sub-cycle reflections of intense laser pulses off oscillating plasma mirrors. I have showed that semi-analytic models—like the saddle-point approach, effective in gas-phase HHG—only partially capture this complexity, and some of the spectral trends. To further improve an analytical representation, I extended the relativistic mirror model to include oblique incidence and uniform proper acceleration for single reflections. Ultimately, full PIC simulations are essential for accurately representing experimental conditions, such as those in the SHHG-SYLOS case [T1, T2].

[I./A] Here in a step by step manner, first I used the concept of the apparent reflection point proposed earlier [29] to formulate an oscillatory integral mimicing the behaviour of the periodic relativistic reflection. Assuming a parabolic time dependence of the reflection point velocity during each emission [29, 31, 32] I employed saddle point based method to check its applicability in predicting the high harmonic scaling showing that only in few special cases, the results match the outcome of PIC simulations. To closely mimic the relativistic reflection via an analytical formulation, I then extended the relativistic mirror model incorporating uniform proper acceleration and oblique incidence. I tested the applicability of this approach by comparing the results with PIC simulations. In order to produce a relativistic structure, which also possesses a high value of reflectivity over the wavelength of the incoming main pulse, one might potentially take advantage of relativistic interaction of high intensity laser and thin solid density plasma. Making use of this derived formula, I attempted to assess the correlation between the properties of the mirror obtained from the PIC simulations and the characteristics of the reflected pulse. The outcomes of the analytical formula are in close agreement with the results of the numerical simulations.

[I./B] I further employed the insight gained, in the context of coherent Thomson backscattering of the light pulse off a relativistic electron mirror. In this scheme, an ultra-strong and short laser pulse irradiates a nanometer thin foil in the blown-out regime of interaction and accelerates a bunch of electrons to relativistic velocities, which is able to partially reflect a counter-propagating pulse. In addition to parametric scan of the influential interaction parameters and their consequences on the interaction dynamics via PIC simulations, it is numerically shown that the frequency upshifting factor of the reflected pulse is correlated with the longitudinal velocity of the electrons, located in the front edge of the relativistic electron bunch.

Point II.

I studied the crucial impact of the waveform of the linearly polarized drive laser on the properties of the generated attosecond pulses through the interaction with the plasma. It was found that a precise control over the delay, energy ratio and the phase of the synthesized drive pulse, consisting of the fundamental and its second harmonic components enables an effective manipulation of the plasma dynamics, which potentially leads to the generation of isolated attosecond pulses in two different schemes of relativistic laser-overdense plasma interactions [T3,C1].

[II./A] Under this point, I have demonstrated that in the relativistic regime, when an intense laser pulse irradiates an overdense plasma surface at oblique incidence, the push–pull electron dynamics at the plasma–vacuum boundary can be effectively tuned by tailoring the driving field waveform. This, in turn, enables substantial control over the HHG process. The temporal delay between the arrival time of the two components of the dual-color incident pulse consists of fundamental frequency 1ω and its second harmonic $(1\omega + 2\omega)$ on target is the influential factor, which impacts the plasma surface dynamics. This parameter was investigated in this thesis by a series of multidimensional relativistic PIC simulations conducted at experimentally realistic and currently achievable laser parameters. After analyzing different combinations of the pulse polarization and strength, it was revealed that a specific delay time introduced in the second harmonic component of the pulse is able to drive an optimal surface plasma dynamics, which gives rise to the generation of an isolated attosecond burst of duration 200asec (in FWHM). Therefore, the two-color multi-cycle field, synthesized with optimized delay and polarization, can all-optically suppress multiple attosecond bursts while selectively allowing a single burst to emerge. This enables the generation of intense, isolated attosecond pulses without the need for complex gating techniques **[T3]**.

[II./B] In the framework of relativistic interaction of intense drive laser with the nanometer-thin foil target, I investigated the impact of precisely tailored driving laser field on characteristics of the generated relativistic electron mirror. It was indicated that an ideally top-hat pulse is able to accelerate electrons into a single dense bunch. However, a Gaussian shaped laser pulse, which is the most commonplace pulse profile on target in the experiments, drives merely the surface electron oscillations and cannot collectively accelerate a single bunch of electrons, as demonstrated in the experiment by Kiefer *et. al.* [28]. Therefore, in order to circumvent this issue of Gaussian-shaped pulse, I proposed to add a portion of the second harmonic component into the pulse and shapes its field waveform. Such optimal two-color Gaussian drive pulse is able to generate a single relativistic electron mirror, which can be utilized to reflect a counter-propagating pulse via Thomson-back scattering process. By using 1D and 2D PIC simulation codes the effect of various driving pulse waveforms and envelopes on the ultrathin foil target and their influence on the back-scattered field was investigated. The key insights of this research were presented in the HILAS conference **[C1]**.

Point III.

In the context of reflection off a relativistic oscillating surface, irradiated by an intense laser pulse, employing the numerical PIC simulations, I investigated different experimental conditions to determine the optimal coupling of the laser and plasma for generating a bright AP. In this framework, I identified two distinct interaction conditions to generate a bright and high efficiency XUV pulses. These interaction regimes are achievable through the real experimental conditions at SHHG-SYLOS beamline at ELI-ALPS [T4].

[III./A] Two key parameters influencing the generation of a bright harmonic beam from plasma surface are: (i) a factor representing light intensification given by the maximum enhancement in the reflected time domain field strength or $\max(a_{ref})/a_0$ and (ii) the conversion efficiency from laser fundamental to high harmonics within a certain spectral range η_{XUV}. I showed that the optimal $\max(a_{ref})/a_0$ and η_{XUV} occur around $\theta_i \sim 50^o - 55^o$ at two different values of plasma gradient scale length $L[\lambda_L]$. These conditions lead to (i) facilitate the generation of a high-efficiency attosecond pulse train, and (ii) to enable the production of an isolated bright AP. The resulting insights were used to guide the selection of appropriate experimental conditions. By analyzing the reflected field structures, it was found that under a specific condition of interaction a single AP can be generated from a multi-cycle incident laser pulse. Therefore, these results manifested the significant impact of the preplasma scale length on the HHG process, which also needs to be taken into account for real experiments.

[III./B] In order to achieve a robust source of bright coherent XUV radiation with sub-femtosecond temporal duration as a probing tool to explore, trace and control ultra-fast electronic dynamics in matters it needs to be well-characterized and well-controlled. I proposed a method to finely adjust the temporal structure of the APs in the train. In the relativistic regime of interaction, the uneven separation of the APs in the reflected pulse train is due to the inward displacement of the reflecting surface during interaction with a laser pulse possessing a Gaussian-shaped envelope. This displacement produces a surface denting, magnitude of which depends on the strength of the corresponding laser pulse field below the Gaussian envelope. With this consideration, the temporal envelope of the incoming Gaussian laser pulse and subsequently the variation of the induced push pressure on the target surface will change the depth of the plasma boundary displacement in every laser cycle, yielding a curved plasma surface. I studied the correlation between the displacement of the plasma boundary in the push phase and the properties of the AP train emitted by electron jets during the pull phase. I showed that a properly chirped drive pulse is able to partially mitigate the harmonic chirp of the reflected AP train. Due to this compensation, the additional beating structures in the reflected radiation spectrum are diminished.

Point IV.

As part of the thesis at ELI-ALPS, I have been able to draw on the computational insights and findings and contribute to the design rationale of the SHHG-SYLOS beamline, its development, and successful implementation. I have presented the experimental results obtained from the relativistic interaction of the full-power SYLOS-3 laser pulse with the liquid leaf target [T2,T4].

[IV./A] I described the procedures that followed to perform the first SHHG experiment at relativistic regime of laser-plasma interaction at ELI-ALPS. I explained various components and the functionality of the SHHG beamline in each unit including the spatio-temporal characterization of the driving beam, the properties of the target and the subsequent diagnostics dedicated to the characterization of the emitted XUV beam. By analyzing and presenting the SHHG spectra, I identified the causes of the instability and lack of reproducibility in the spectra of the reflected radiations. Therefore, within the next experimental campaign of SHHG, efforts were made to resolve the two major contributing factors to this issue. In Figure 2, the generation of harmonics above the CWE cut-off frequency substantiates the relativistic interaction of the laser pulse with the liquid leaf target.

[IV./B] The efficiency and spatio-spectral characteristics of surface high order harmonic generation can be precisely controlled by tailoring the plasma density gradient, thereby establishing it as a key control parameter in the optimization of relativistic plasma mirror applications. The experimental observations of shaping the plasma profile by tuning the delay time between the prepulse and the main pulse was presented and discussed. At each value of delay in the range of $\tau \in [-1, 20]$ps, the spectrum of the reflected radiation was recorded and analyzed. Figure 3 illustrates the spectral map of the emitted radiation as per variation of the delay for two different cases of incident beam diameters and peak intensities.

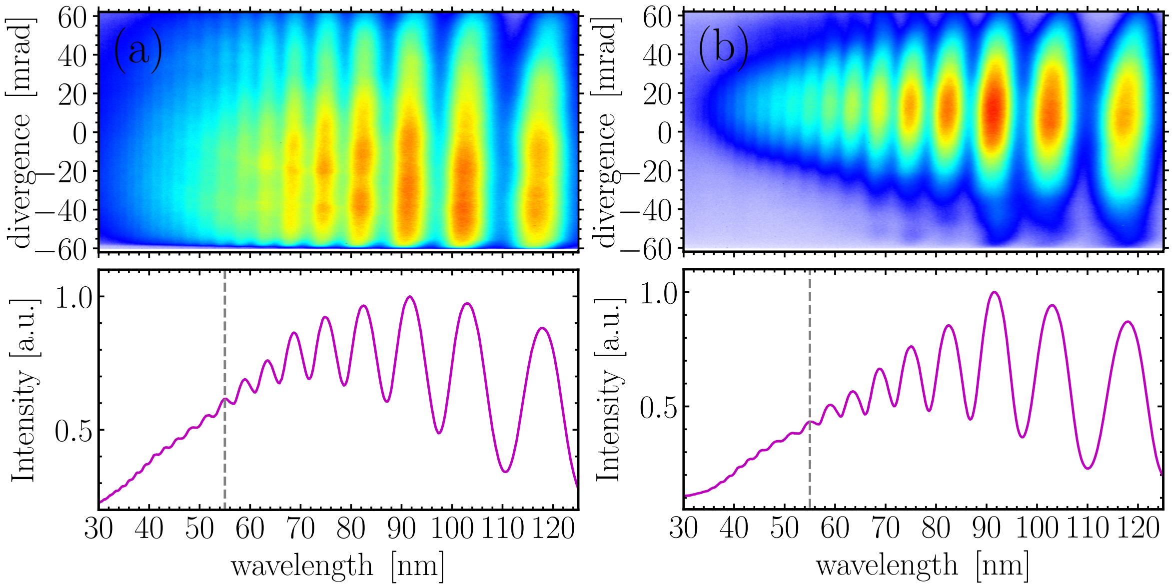

Figure 2: *Recorded SHHG spectrum at improved experimental conditions. Column (a) is the spectrum of the emitted radiation through interaction of full size beam (*65*mm diameter with peak intensity of* $\simeq 3 \times 10^{19}$*Wcm*$^{-2}$ *and* $a_0 \simeq 3.5$*) with the leaf target, while the main beam is irised to an aperture size of* 40*mm (with the estimated peak intensity of* $\simeq 4 \times 10^{18}$*Wcm*$^{-2}$ *and* $a_0 \simeq 1.8$*) in column (b). Top panel is the spatio-spectral characteristic of the emitted harmonic beam on the phosphor screen imaged by the camera and calibrated to wavelength axis. The bottom panel is the calibrated lineout, integrated over* 120*mrad transverse divergence of the spectrum. The spatial divergence of the incident laser focused on the target is* 600*mrad and* 400*mrad for the case of full and the apertured beam, respectively. Both results in (a) and (b) were recorded at the same prepulse delay* τ = 5*ps, implying an identical initial plasma profile before the onset of the relativistic interactions. The vertical dashed lines mark the plasma cut-off wavelength, which is corresponding to the electron density of a fully ionized liquid target.*

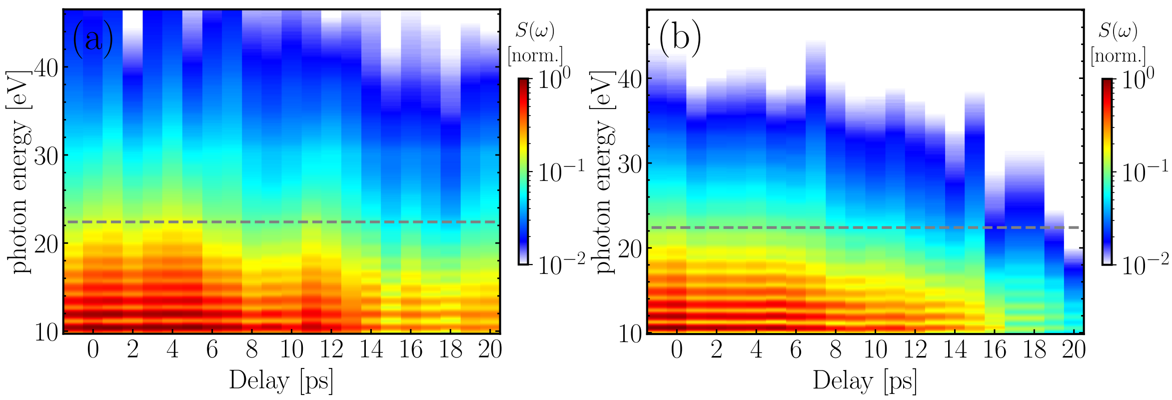

Figure 3: *Experimental observation of the influence of variation of the prepulse delay on the SHHG spectrum. (a) shows the spectral map for the full size beam (with* 65*mm diameter) interacting with the liquid leaf at different delay of prepulse* τ*. The spectral map of the irised beam (with diameter* 40*mm) interacting at different delay of prepulse is plotted in panel (b).*

Publications

Own publications

[T1] Nayak Arjun, Dumergue Mathieu, Kühn Sergei, Mondal Sudipta, Csizmadia Tamás, Harshitha N.G., Füle Miklós, Upadhyay Kahaly Mousumi, Farkas Balázs, Major Balázs, Szaszkó-Bogár Viktor, Földi Péter, Majorosi Szilárd, Tsatrafyllis Nikolaos, Skantzakis Emmanuel, Neoričić Lana, **Shirozhan Mojtaba**, Vampa Giulio, Varjú Katalin, Tzallas Paraskevas, Sansone Giuseppe, Charalambidis Dimitris, Kahaly Subhendu. Saddle point approaches in strong field physics and generation of attosecond pulses. *Physics Reports*, 833(11), 1–52, 2019. (Impact factor: 29.03)

[T2] Mondal Sudipta, **Shirozhan Mojtaba**, Ahmed Naveed, Bocoum Maïmouna, Boehle Frederik, Vernier Aline, Haessler Stefan, Lopez-Martens Rodrigo, Sylla François, Sire Cedric, Quéré Fabien, Nelissen Kwinten, Varjú Katalin, Charalambidis Dimitris, Kahaly Subhendu. Surface plasma attosource beamlines at ELI-ALPS. *Journal of the Optical Society of America B*, 35(5), A93, 2018. (Impact factor: 2.05)

[T3] Mondal Sudipta, **Shirozhan Mojtaba**, Choudhary Shivani, Nelissen Kwinten, Tzallas Paraskevas, Charalambidis Dimitris, Varjú Katalin, Kahaly Subhendu. Intense isolated attosecond pulses from two-color few-cycle laser driven relativistic surface plasma. *Scientific Reports*, 12(1), 2022. (Impact factor: 3.9)

[T4] **Shirozhan Mojtaba**, Mondal Sudipta, Grósz Tímea, Nagyillés Balázs, Farkas Balázs, Nayak Arjun, and Ahmed Naveed, Dey Indranuj, De Marco Shivani Choudhary, Nelissen Kwinten, Kiss Miklos, Oldal Lénárd Gulyás, Csizmadia Tamás, Filus Zoltán, De Marco Massimo, Madas Saibabu, Kahaly Mousumi Upadhyay, Charalambidis Dimitris, Tzallas Paraskevas, Appi Elisa, Weissenbilder Robin, Eng-Johnsson P., L'Huillier Anne, Diveki Zsolt, Major Balázs, Varjú Katalin, Kahaly Subhendu. High-Repetition-Rate Attosecond Extreme Ultraviolet Beamlines at ELI ALPS for Studying Ultrafast Phenomena. *Ultrafast Science*, 4(1), 2024. (Impact factor: 9.9)

Cumulative impact factor: 44.88

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[T6] **Shirozhan Mojtaba**, Mondal Sudipta, Hack Szabolcs, Czirják Attila, Upadhyay Kahaly Mousumi, Dey Indranuj, Nelissen Kwinten, Kahaly Subhendu. Controlling Relativistic Electron Mirror Dynamics for tunable single Attosecond pulse generation. *arXiv*, 2025.

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[C1] **Shirozhan Mojtaba**, Kahaly Subhendu. *Waveform-dependent Single Attosecond Pulse Generation via Thomson Back-scattering Process*. High Intensity Lasers and High Field Phenomena (HILAS): Proceedings High Brightness Sources and Light-driven Interactions, *Optica Publishing Group*, DOI: 10.1364/HILAS.2022.HF3B.7, 2022.

[C2] **Shirozhan Mojtaba**, Kahaly Subhendu. *Intense attosecond pulses from relativistic interaction of few cycle lasers with plasma mirrors*. High Intensity Lasers and High Field Phenomena (HILAS): Proceedings High-Brightness Sources and Light-driven Interactions, *Optica Publishing Group*, DOI: 10.1364/HILAS.2018.HM2A.5, 2018.

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Spatio-temporal Optimization of the Focal Spot for Relativistic High Harmonic Generation.
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[P2] Shirozhan Mojtaba, Ahmed Naveed, Choudhary Shivani, Nelissen Kwinten, Mondal Sudipta, Kahaly Subhendu.
Controlling the Attosecond Pulse Train in Few Cycle Laser Driven Relativistic Surface Plasma.
The 3th International Conference on Extreme Light (2019).

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