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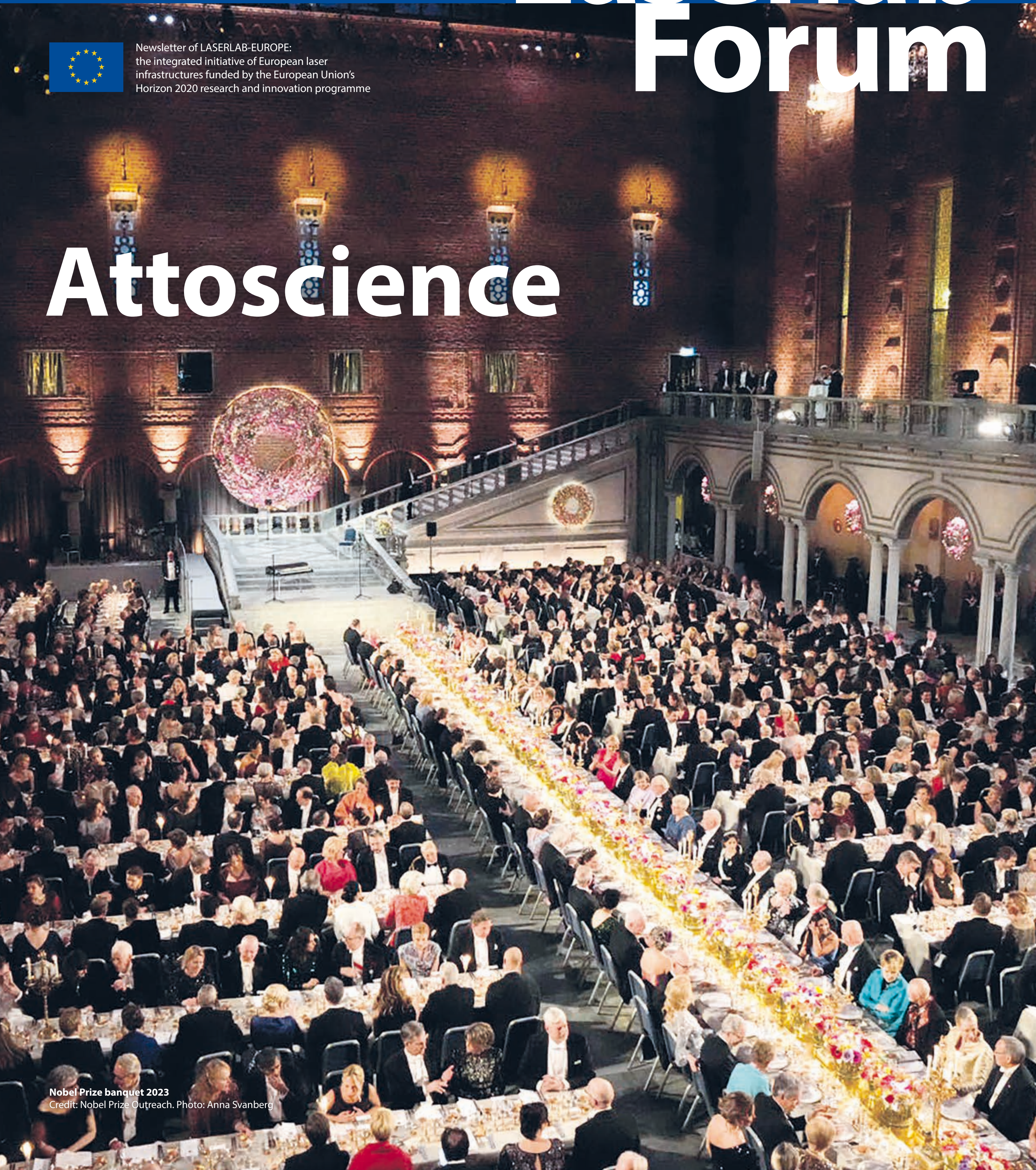
Laserlab Europe

Laserlab Forum

Newsletter of LASERLAB-EUROPE: the integrated initiative of European laser infrastructures funded by the European Union's Horizon 2020 research and innovation programme

Attoscience



Nobel Prize banquet 2023
Credit: Nobel Prize Outreach. Photo: Anna Svanberg

Editorial

Sylvie Jacquemot

Our community recently erupted in celebration when Anne L'Huillier, Pierre Agostini, and Ferenc Krausz, all engaged with Laserlab-Europe labs, now or in the past, were honored with the prestigious Nobel Prize in Physics. Their ground-breaking contributions have paved the way for revolutionary advances in laser science.

In celebration of these remarkable achievements, this Laserlab Forum is entirely devoted to the fascinating subject of attoscience. The following articles highlight current studies conducted within our consortium. As attoscience allows capturing and manipulating phenomena that occur in incredibly short periods of time, not only does it enable discovering the inner workings of atoms and molecules with unprecedented precision, it also has far-reaching implications for a wide range of fields, from chemistry and physics to biology and materials science.

Enjoy reading and I hope to see you in person at the Laserlab-Europe Conference in Lisbon at the end of May!

Sylvie Jacquemot

News

360 CARLA photonics career launch programmes

Building on the success of the CARLA project in 2020-2022, the new 360 CARLA project was launched in January: A comprehensive career development initiative aimed at shaping the future of photonics professionals. The project brings together a consortium of 12 partners, including ICFO (coordinator of the project), Photonics Austria, Max Born Institute, Politecnico di Milano, Institut d'Optique, International Laser Centre, Vrije Universiteit Brussel, Delft University of Technology, Photonics Sweden, Photonics Finland, European Optical Society, and SwissPhotonics as an associated partner.

The 360 CARLA project is a 2.5-year European Union-funded endeavour that aspires to create cohesive career development programmes focusing on four application verticals: health (biotech and medical photonics), quantum technologies and communications, energy, environment, and sustainability, and manufacturing and industry 4.0. Key components of the 360 programmes encompass themed symposiums in a hybrid format, inspired by the successful CARLA camps. Additionally, specialised training workshops and company visits aim to enrich innovation and entrepreneurship experiences.

EURIZON fellowship programme for Ukraine begins

In February, the EU Project EURIZON kicked off its fellowship programme for scientists in Ukraine. An exceptional number of more than 780 proposals have been submitted. To accommodate this overwhelming response, the EU Commission tripled the initial budget from 1.5 million to 4.5 million euro. This increase provides the opportunity to fund approximately 60 projects involving about 300 scientists.

EURIZON Project

By now, a total of 65 research teams have been identified across three selection shifts within this programme. As a result, 324 scientists in Ukraine will be awarded individual grants that will support their scientific work at their home institutions in Ukraine and boost international collaborations, even amidst the difficult conditions of ongoing attacks. The Russian invasion has seriously disrupted scientific work in Ukraine. Funding for scientific projects has been cut or reduced, posing a threat to science. Moreover, attacks have damaged or destroyed education and research facilities in many areas of the country.

EURIZON is an EU-funded project that involves 27 European research institutes including Laserlab-Europe, coordinated by DESY. Their main aim is to encourage collaboration among European research centres and to support research efforts in Ukraine.

What is Laserlab-Europe?

Laserlab-Europe, the Integrated Initiative of European Laser Research Infrastructures, understands itself as the central place in Europe where new developments in laser research take place in a flexible and co-ordinated fashion beyond the potential of a national scale. The Consortium currently brings together 35 leading organisations in laser-based inter-disciplinary research from 18 countries. Additional partners and countries join in the activities through the association Laserlab-Europe AISBL. Its main objectives are to maintain a sustainable inter-disciplinary network of European national laboratories; to strengthen the European leading role in laser research through Joint Research Activities; and to offer access to state-of-the-art laser research facilities to researchers from all fields of science and from any laboratory in order to perform world-class research.

Platform for laser-driven ion acceleration: A collaborative effort at HiLASE facility

Lorenzo Giuffrida from ELI Beamlines

An experimental platform for laser-driven ion (sub-MeV) acceleration and potential applications was commissioned recently at the HiLASE laser facility in the Czech Republic. Utilising the Bivoj laser system, the platform demonstrates stable production of high-current ion beams of multiple species (Al, Ti, Fe, Si, Cu, and Sn), operating at gigawatt peak power levels and 1–10 Hz repetition rates. The produced laser-plasma ion sources were fully characterized against the laser intensity on the target (10^{13}–10^{15} W/cm^2) by varying the laser energy, focal spot size, and pulse duration.

The collaborative effort of researchers from HiLASE, ELI Beamlines Facility, CTU, FBK, and others underscores the importance of national and international collaborations, and culminated in a paper titled "A Platform for Laser-Driven Ion Sources Generated with Nanosecond Laser Pulses in the Intensity Range of 10^{13}–10^{15} W/cm^2" published in the journal Quantum Beam Science.

https://doi.org/10.3390/qubs8010005

Jena research team develops AI system in optical fibers

Researchers from the Leibniz Institute of Photonic Technology (Leibniz IPHT) in Jena, Germany, along with an international team, have developed a new technology utilising light for neuronal computing, inspired by the human brain's neural networks. Published in "Advanced Science," their work introduces a novel approach that could significantly decrease the energy demands of future AI systems while enhancing data processing speed. Unlike traditional systems relying on electronic components, their method employs a single optical fibre to mimic the computational power of multiple neural networks at the speed of light. By encoding data onto light pulses within the fibre, the system can efficiently process vast amounts of information, enabling applications ranging from intelligent microscopy to computerless diagnostics. This innovation holds promise for environmentally friendly AI applications and represents a significant step towards energy-efficient computing systems.

Sven Döring/ Leibniz IPHT

Detector patented for single-shot, high repetition rate CEP detection

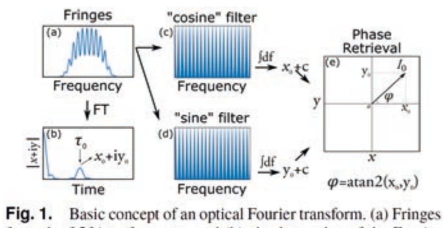


Fig. 1. Basic concept of an optical Fourier transform. (a) Fringes from the f-2f interferometer and (b) absolute value of the Fourier transform of the signal; panels (c) and (d) illustrate sine- and cosine-like filters that are used to perform the partial Fourier transform from which the phase φ can be obtained as the arctan between x_0 and y_0 as illustrated in panel (e), with background c removed.

Figure from Chen Guo et al., Opt. Lett. 48, 5431-5434 (2023)

The carrier-envelope offset phase (CEP) is an important parameter, determining light-matter interaction for few-cycle laser pulses. Its precise characterisation is essential for attosecond physics and frequency-comb spectroscopy. With the constant advance of laser technology, few cycle sources with high average power and high repetition rate have become commonly available.

Conventionally, CEP measurements via f:2f spectroscopy are hard to scale up, because of two main bottlenecks: First, the physical measurement of optical spectra at up to MHz repetition rates and second, mathematical Fourier transform operations, to numerically extract the CEP from the recorded spectra.

In a recent publication in Optics Letters, a team of researchers from Lund University and from the company Sphere Ultrafast Photonics proposed a pioneering detection scheme that circumvents these challenges by performing the Fourier transform optically. As a result, the CEP is obtained from just two photodiode signals. Measuring the CEP of every pulse, instead of averaging, can tremendously improve CEP-stabilisation schemes as well as be used to tag the CEP for every pulse in a measurement, thus performing CEP dependent measurements with un-stabilised lasers.

https://doi.org/10.1364/OL.498664

Breakthrough in ultraviolet spectroscopy

Researchers in the group of Nathalie Picqué at the Max Planck Institute of Quantum Optics (MPQ) and at the Max Born Institute (MBI) have achieved a groundbreaking advancement in ultraviolet spectroscopy by successfully implementing high-resolution linear-absorption dual-comb spectroscopy in the ultraviolet spectral range. Published in the scientific journal Nature, their work introduces a novel technique capable of detecting and quantifying multiple substances with high chemical selectivity even under low-light conditions. This breakthrough opens up new avenues for novel applications of photon-level diagnostics, such as precision spectroscopy of single atoms or molecules for fundamental tests of physics and ultraviolet photochemistry in the Earth's atmosphere or from space telescopes.

https://doi.org/10.1038/s41586-024-07094-9

MPQ

ERC Grants

Each year, Laserlab-Europe researchers are awarded prestigious grants by the European Research Council (ERC). Here, we highlight six Advanced Grant projects – worth up to 2.5 million euro, with a runtime of five years.

Thomas Stoehlker (GSI): Highly ionised trapped 229-thorium: A new paradigm towards a nuclear clock


HI Jena

Currently, there are intense research activities in many laboratories worldwide related to the "thorium clock" since such a "nuclear clock" opens new doors to fundamental physics such as e.g. testing time-variations of natural constants and exploring the enigma of dark matter. This may, in the long run, even enable the establishment of a new time standard. Thomas Stoehlker's project "HITHOR" is a novel access to the "thorium clock" with the focus on highly-ionized 229-thorium, an elementary quantum-system, which consists only of the thorium nucleus and one or few electrons.

Thomas Udem (MPQ): High resolution laser spectroscopy of atomic hydrogen and deuterium


Thomas Udem

The standard model of particle physics explains how the world is organised at the smallest scale. However, it does not fit all physical observations. One approach to testing the model is to measure physical processes ever more precisely and to determine the constants of nature ever more accurately. With his ERC Advanced Grant, Thomas Udem wants to measure the energies for selected excitations of a hydrogen atom with unprecedented precision. To this end, he and his team will develop an optical trap for hydrogen atoms. In this trap, they can fix atomic hydrogen in such a way that its excitation can be determined with particular precision.

Javier García de Abajo (ICFO): Quantum-enhanced free-electron spectromicroscopy


ICFO

In his project QUEFES, Javier García de Abajo will introduce a conceptually disruptive approach to capitalise on the quantum nature of free electrons and their interactions with matter and radiation fields aiming to obtain previously inaccessible information on the atomic-scale dynamics of such materials, to reveal hidden properties of the quantum vacuum, and to control the many-body state of quantum matter.

Roberta Croce (LLAMS): Photosynthesis in far-red: from cyanobacteria to plants

When plants grow close together, the lower leaves receive almost exclusively far-red light, which has been thought to be unusable for oxygenic photosynthesis. Recent discoveries, however, show that certain cyanobacteria, the ancestors of plant chloroplasts where photosynthesis takes place, can grow under far-red light. This is where Roberta Croce comes in: She receives an Advanced Grant for her research project "Fared Well", through which she aims to learn from those bacteria how to improve plant photosynthesis.

Johannes de Boer (LLAMS): Immuno-optical coherence tomography


Peter Valkcx

In the early stages, tumours are too small to be visible with PET and CT. Optical techniques have a much higher resolution and can detect tumours at a much earlier stage. With his ERC Advanced Grant, Johannes de Boer will develop a new optical endoscopic imaging technique to detect cancer in the human body with a resolution 10 to 100 times higher than currently possible. The major challenge is to develop very small motorised catheters that can penetrate deep into the body to determine both the structure and the molecular composition of tissue with light.

Sandrine Lévêque-Fort (ISMO): Time-based single molecule nanolocalisation for live cell imaging

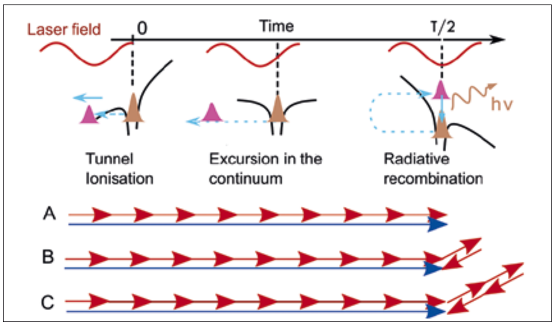

Emmanuel Fort

Sandrine Lévêque-Fort has been awarded an ERC Advanced Grant for her project TimeNanoLive. While current approaches based on the localisation of individual fluorescent molecules allow for observations on the nanometre scale, the current localisation process of these molecules is slow and often limited to the observation of non-living cells. TimeNanoLive aims to revolutionise localisation by using a specific structured illumination to encode the 3D position of fluorescent molecules with increased spatial and temporal resolution.

Focus: Attoscience

Attoscience empowers the observation and control of phenomena transpiring within infinitesimal timeframes. In celebration of the remarkable achievements by the recent Nobel laureates in Physics, this Laserlab Forum is exclusively dedicated to the captivating realm of attoscience. Presented within are a series of articles spotlighting ongoing investigations carried out within our consortium.

High harmonic generation: from strong field physics to photon pathways (LIDYL, France)



(Top section) Three-step model of HHG. (Bottom section) The identified processes for the generation of the q=9th harmonic. Scheme A corresponds to the usual description of nonlinear optics, involving q photons from the driving laser to produce the qth harmonic. Schemes B and C involve a second laser beam, non-collinear with the first one, with one and two additional photon pairs, respectively, interfering with the first one. Depending on the intensity of this second beam, these, or even higher order processes, may become the dominant pathways. HHG is thus generally the result of interference from numerous "photon pathways," explaining the peculiar behaviour of its yield.

The ability to produce flashes of light of attosecond duration currently relies on gas phase high harmonic generation (HHG), the cornerstone of attosecond science. HHG is generally explained as the interaction of a very intense classical laser field with matter. Modelling this with a fully classical simulation, the strong field approximation, or directly solving the time-dependent Schrödinger equation, three steps are identified (as shown in the figure): partial ionisation of matter, which occurs close to the maximum of the laser beam's electric field; acceleration of the ionised part of the electronic wave packet by the same laser field; and, if it passes close to the ionic core, recombination with the parent ion. During this final step, the electronic wave packet releases its excess of kinetic energy in the form of extreme ultraviolet radiation. This three-step model is extremely useful for predicting many properties of HHG, such as its efficiency, its spectral extension in relation to the laser parameters, and its response to various polarisations. However, until now, no description of HHG in terms of "photon pathways" has appeared entirely satisfactory, especially in terms of predicting yield.

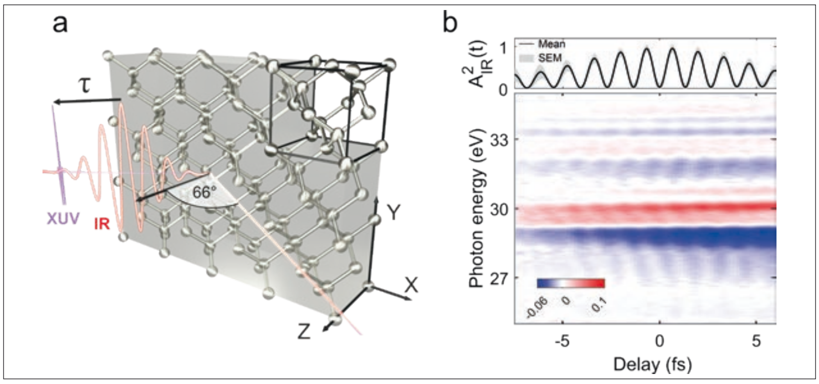
A new experiment, conducted in LIDYL (CEA-Saclay), addressed this problem. It was shown that the generation of a given harmonic by HHG results from the coherent addition of multiple interfering processes. Beyond the minimum number of photons required to produce a given harmonic, additional photon pairs, associated with the combination of absorption and stimulated emission, come into play. A very simple model counting the different contributing pathways was proposed, and closely agreed with the experimental results. These results may prove a decisive step in the long quest for a "photonic picture" of HHG, offering new insights into the quantum processes at play in the strong-field regime.

Thierry Ruchon, Mekha Vimal, Martin Luttmann, Titouan Gadeyne, Matthieu Guer, Romain Cazali, David Bresteau, Fabien Lepetit, Olivier Tcherbakoff, Jean-François Hergott, Thierry Auguste, Titouan Gadeyne, Céline Chappuis and Jean-François Hergott (LIDYL)

M. Vimal et al., Phys. Rev. Lett. 131: 203402 (2023)
M. Luttmann et al., Phys. Rev. A 108: 053509 (2023)

Field-driven attosecond charge dynamics in germanium (CUSBO, Italy)

In recent years, attosecond science has made it possible to investigate electron dynamics in matter triggered by ultrashort pulses on their native timescale, namely the attosecond regime. Being able to use light pulses to follow and control ultrafast electron dynamics in matter is a long-sought goal, with important implications in many fields of technology and research. In a semiconductor, for example, charge injection by few-femtosecond infrared (IR) pulses could be used to turn the material into a conductive state, realising ultrafast switches in opto-electronics, a milestone that promises to increase the limiting speed of data processing and information encoding. This technological breakthrough can only stem from a comprehensive knowledge of light-induced charge injection, a key challenge of modern solid-state physics and photonics.



a *Schematic representation of the pump–probe measurement where the ultrafast dynamics induced by a few-fs IR pulse are probed through the reflected attosecond radiation.*
b *Experimental differential reflectivity trace ΔR/R for the germanium sample (main panel) and squared modulus of the simultaneously measured pump vector potential (top panel).*

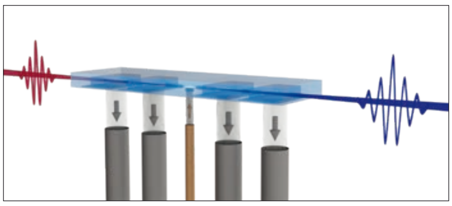
Figure from Inzani et al, Nature Phot. 17, 1059 (2023)

A study, recently published in *Nature Photonics,* tackled this problem by investigating field-driven carrier injection in a prototype semiconductor (monocrystalline germanium) with attosecond transient reflection spectroscopy. By monitoring the reflectivity of the sample around the $M_{4,5}$ edge (~ 29.5 eV), a new light-matter interaction regime was discovered where charges are excited by diverse coexisting mechanisms, which compete and develop on different timescales, of the order of few femtoseconds. Both ultrafast transient and long-lasting features of the sample reflectivity were observed, which cannot be ascribed to a single physical mechanism. Detailed numerical simulations, based on advanced theoretical models, allowed the ultrafast charge injection to be mapped in momentum and time, and revealed a complex interaction between various processes in the quantum-mechanical response of the material that had never been observed before. This discovery suggests that it is possible to act on the light properties to control the diverse mechanisms on these extreme timescales, to optimise charge injection while reducing the energy exchange with the material: a fundamental result for the development of next-generation electro-optical devices.

Mauro Nisoli, Matteo Lucchini (CUSBO)

G. Inzani et al., Nature Photonics 17: 1059–1065 (2023)

Advancements in ultra-broadband and efficient UV light pulse generation for attochemistry (DESY, Germany)



Pasquale Barbato, IFN-CNR, Milan

Graphical representation of the novel microfluidic chip. Gas is injected into the central generation cell of the chip, where it interacts with the NIR driving field, producing UV pulses through third-harmonic generation. Simultaneously, the gas is evacuated via four differential-pumping chambers to prevent reabsorption of the generated UV radiation.

Attochemistry is gradually shifting its focus from the study of charge migration and charge transfer in ionised molecules, to the study of the role of electron dynamics in the photochemistry of molecules activated by ultraviolet (UV) light [1]. In particular, UV light is respo nsible for the excitation of valence electrons, which leads to chemical changes on longer timescales that are relevant in nature.

The generation of ultra-short UV pulses poses a major challenge, as material dispersion in this spectral range is unfavourable. The development of novel UV light sources has enabled the generation of ever shorter light pulses, down to a duration of a few femtoseconds. In 2019, sub-2 fs pulses were successfully generated in argon and neon using a technique developed by Francesca Calegari's group at DESY (Hamburg, Germany), based on the third-harmonic frequency conversion of few-cycle near-infrared (NIR) laser pulses in a high-density gas [2]. Although this technique succeeded in setting a world-record for the shortest UV pulses ever generated, it suffered from low conversion efficiency due to the relatively low gas confinement achieved in the generation setup. In parallel to this work, Travers' group at Heriot-Watt University (Edinburgh, UK) demonstrated the possibility of frequency converting NIR pulses into deep UV pulses in a gas-filled hollow capillary using the resonant dispersive wave approach [3]. This technique allows for a relatively high conversion efficiency and spectral tuneability, but at the expense of a non-compact setup. Using this approach, the generation of sub-3 fs UV pulses has been demonstrated [4].

In work recently published in the *Journal of Physics: Photonics,* Francesca Calegari's group has now demonstrated the efficient generation of ultra-broadband femtosecond UV pulses (200-325 nm), using a dual-stage differential-pumping scheme integrated into a glass microfluidic chip that provides an exceptional gas confinement up to several bars in a high-vacuum environment [5]. As in [2], the novel microfluidic chip is fabricated using the FLICE (femtosecond laser irradiation and chemical etching) technique [6]. By delivering UV supercontinua supporting sub-2 fs durations, as well as pulse energies comparable to capillary-based techniques, this compact device makes a step towards the production and application of sub-fs UV pulses for the real-time investigation of electron dynamics in neutral molecules. These ultrashort UV pulses are currently available for Laserlab-Europe users in the attosecond science laboratory of Francesca Calegari at DESY.

Francesca Calegari (DESY)

[1] F. Calegari and F. Martin, Commun. Chem. 6: 184 (2023)
[2] M. Galli et al., Opt. Lett. 44: 1308–11 (2019)
[3] J.C. Travers et al., Nat. Photonics 13: 547–54 (2019)
[4] M. Reduzzi et al., Opt. Express 31: 26854–26864 (2023)
[5] V. Wanie et al., J. Phys. Photonics 6: 025005 (2024)
[6] R. Osellame et al., Laser Photon. Rev. 5: 442–63 (2011)

Attosecond core-level soft-x-ray spectroscopy at ICFO (Spain)

Photochemical reactions are complex, involving many different dynamical processes. Very often, the strongly coupled electron and nuclear dynamics procedure via conical intersections leads to induce radiationless relaxation. Such dynamics form the basis of a lot of relevant biological and chemical functions, but are challenging to resolve. Difficulties arise when trying to trace nuclear and electronic motion simultaneously, as their dynamics are complicated and difficult to disentangle, and occur at comparable ultrafast timescales.

To address these challenges, the ICFO team has developed attosecond core-level spectroscopy [1-3] to investigate molecular dynamics [4] in real-time. The method was benchmarked by tracing the evolution of gas-phase furan, an organic carbon, hydrogen and oxygen compound arranged in a pentagonal geometry. The choice of compound was not arbitrary: furan is the prototype for studying heterocyclic organic rings, essential constituents of many different day-to-day products, such as fuels, pharmaceuticals, and agrochemicals. The team was able to time-resolve the details of the entire ring-opening dynamics of furan, specifically the excitation and flow of energy leading to the fission of the bond between one carbon and the oxygen that breaks the cyclical structure. This was achieved by tracking several conical intersections – the ultrafast gateways between different energy states that furan undertakes in its evolution towards ring-opening [4]. Results show that attosecond core-level soft-x-ray spectroscopy is able to disentangle the many-body interactions [5] between carriers and nuclei; the technique can identify

Figure 1 and Figure 2: Adapted from A.M. Summers et al., Ultraf. Sci. 3, 4 (2023) and S. Severino et al., arxiv:2209.04330, Nature Photonics *https://doi.org/10.1038/s41566-024-01436-9*

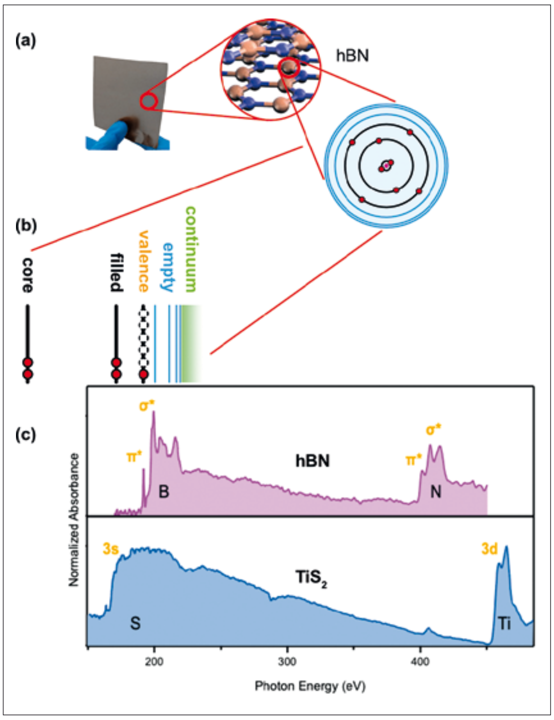


Figure 1: Coherent ultrabroad spectrum of an isolated attosecond SXR pulse [1] measures the complete electronic structure of all components of a material. Examples are shown for hBN and TiS_2 [3].

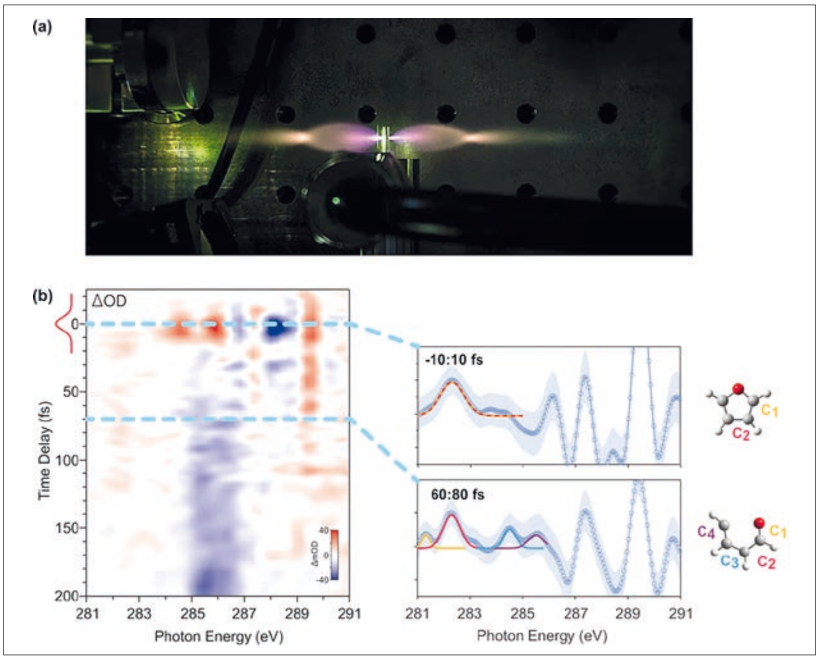


Figure 2: (a) Picture of a 2-micron, sub-2-cycle laser pulse interaction in high-pressure helium to generate an isolated 23 as pulse [2]. (b) The entire electron-nuclear dynamics are encoded in the time-energy measurement of furan. Lineouts show the absorption of a pump photon (top). It takes circa 60 fs for the bond to break. The four non-identical bonds of the open ring appear as four peaks in the SXR spectrum [4].

electronic and nuclear coherences, quantum beats, optically dark states, and symmetry changes, providing a highly detailed picture of the whole relaxation process.

The described methodology promises deeper insight into long-standing problems related to technological issues, such as inefficient energy conversion and storage in light-harvesting or catalysis. Using the quantum coherence of the light-matter interaction will deliver a tool that will be able to address many exciting fundamental and applied questions of significant importance to science and technology.

Jens Biegert (ICFO)

[1] S.L. Cousin et al., Opt. Lett. 39: 5383 (2014)
[2] S.L. Cousin et al., Phys. Rev. X 7: 041030 (2017)
[3] A.M. Summers et al., Ultraf. Sci. 3: 4 (2023)
[4] S. Severino et al., arxiv:2209.04330, Nature Photonics *https://doi.org/10.1038/s41566-024-01436-9*
[5] T.P.H. Sidiropoulos et al., Nature Comm. 14: 7407 (2023)

Attosecond sources for applications (LLC, Sweden)

Coherent radiation in the extreme-ultraviolet (XUV) to soft X-ray spectral range, produced by high-order harmonic generation (HHG), is useful in a number of applications, including attosecond science and nanoscale imaging. The radiation source may be optimised to target different properties, such as overall efficiency, the time structure (single attosecond pulses or trains of pulses), coherence properties or the ability to focus to a small spot size, and high peak intensity, to suit the application.

Today, many different laser technologies drive HHG sources, including chirped pulse amplifiers (CPAs), optical parametric CPAs, and post-compressed CPAs, with driving wavelengths from the ultraviolet to the infrared. Alongside this, a large variety of generation geometries exist, such as short and dense gas jets, long and dilute gas cells, semi-infinite cells, and gas-filled capillaries. Despite thirty years of collective experience in the community, there is still no general consensus on the optimum configuration.

A team from LLC has worked with academic and industrial collaborators to develop models that describe, in simple terms, the essential physics of HHG [1-4]. The influence of macroscopic parameters on the conversion efficiency has been investigated, such as medium length, medium position, pressure, and intensity of the driving laser [3, 5]. The relation between pressure and length corresponding to a high conversion efficiency follows a hyperbolic shape (see Figure 1). The model underpins the large variety and versatility in gas target designs used in the community.

The small structure size of modern lithography, in connection with the ongoing change of illumination wavelength to 13.5 nm, requires novel, compact, high brightness and high spatial coherence sources in the extreme-ultraviolet for structure metrology. Other aspects of HHG source development, like divergence and focus area, are also important for attosecond-pump/attosecond-probe experiments, where a high focused intensity is essential to achieve non-

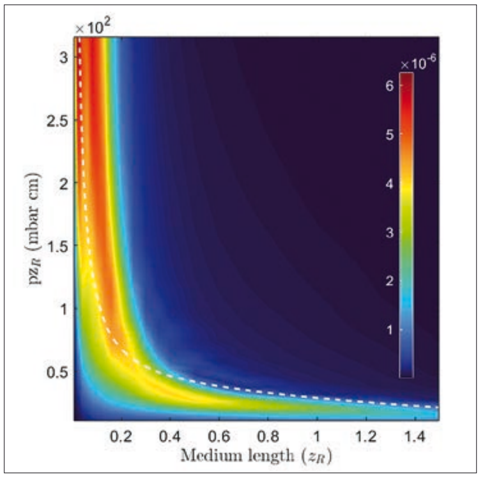


Figure 1: Simulated HHG conversion efficiency for the 23rd harmonic in argon for different pressures and medium lengths at a driving laser intensity of $I = 2.5 \times 10^{14}$ W/cm². The medium was centred at the laser focus; both axes are normalised for scalability (z_R is the Rayleigh length). The analytical hyperbola model (dashed line) predicts configurations of high conversion efficiency with good accuracy. The horizontal branch represents HHG in gas cells, the vertical branch the conditions in gas jets.

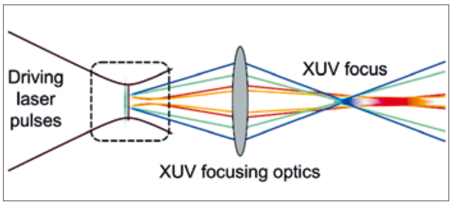


Figure 2: Spatiotemporal couplings of attosecond pulses upon refocusing. In the Gaussian beam model, the placement of the gas target relative to the geometrical focus of the driving laser determines the wavefront and divergence of individually generated harmonics. Depending on the order, the harmonics can originate from real or virtual source points and can have very different divergences; upon re-focusing, this results in complicated spatiotemporal couplings and impairments of the maximum intensity.

linear interaction with the target. A simplified, semi-classical model of HHG [1, 2] has been developed that provides the basic spatial and spatiotemporal properties of the generated radiation, and describes individual harmonics in terms of Gaussian beams. The model shows the divergence and focusing properties of individual harmonics (see Figure 2), as well as the spatiotemporal properties of the attosecond pulse trains [6]. Moreover, it offers insights into how impairments, like ellipticity and astigmatism, in the driving laser impact the attosecond pulses generated, and how to optimise the source properties by manipulating the driving laser [4, 7].

Cord L. Arnold, Per Eng-Johnsson, Johan Mauritsson, Anne-Lise Viotti, Anne L'Huillier (LLC)

[1] C. Guo et al., J. Phys. B: At. Mol. Opt. Phys. 51: 034006 (2018)
[2] H. Wikmark et al., Proc. Nat. Am. Sci. (PNAS) 116: 4779 (2019)
[3] R. Weissenbilder et al., Nat. Rev. Phys. 4: 713 (2022)
[4] M. Plach et al., Ultrafast Sci. 4: 0054 (2024)
[5] E. Appi et al., Opt. Express, 31: 31687 (2023)
[6] M. Hoflund et al., Ultrafast Science 9797453 (2021)
[7] K. Veyrinas et al., N. J. Phys. B 25: 023017 (2023)

All-attosecond pump-probe spectroscopy (MBI, Germany)

The development of femtochemistry towards the end of the 20th century made it possible to study the dynamics in a chemical reaction in real time. For the first time, the motion of atoms in the process of forming or breaking bonds could be observed. Ahmed Zewail was awarded the Nobel Prize in Chemistry 1999 for his pioneering work in this field. The first demonstration of attosecond pulses at the beginning of the 21st century, which was awarded the Nobel Prize in Physics 2023, allowed access to the observation of electron dynamics in matter, which move on even faster timescales. However, up to now most attosecond experiments performed have been limited by the fact that one attosecond pulse is typically combined with one femtosecond pulse, the oscillating field of the latter serving as a clock to obtain attosecond time resolution.

Since attosecond pulses were first demonstrated, many scientists have aspired to perform experiments in which a first attosecond pump pulse initiates dynamics in an atom, a molecule or a solid, and a second attosecond probe pulse interrogates the system at different time delays. Recent work has brought this goal within reach.

An experiment using a synchronized attosecond x-ray pulse pair from an x-ray free-electron laser (the Linac Coherent Light Source (LCLS)) has recently been reported [1]; here, a single snapshot rather than an entire movie was recorded. In other work, the development of table-top attosecond-pump attosecond-probe spectroscopy (APAPS) has recently resulted in a breakthrough at the Max Born Institute (MBI). Following the first demonstration of APAPS at kilohertz repetition rates (see Figure 1) [2], researchers from the MBI have recently conducted the first table-top all-attosecond transient absorption spectroscopy (AATAS) experiment.

These recent developments not only mark the beginning of a new chapter for attochemistry, but also have the potential to enable the study of extremely fast electron dynamics in atoms, molecules and solids from an entirely new perspective.

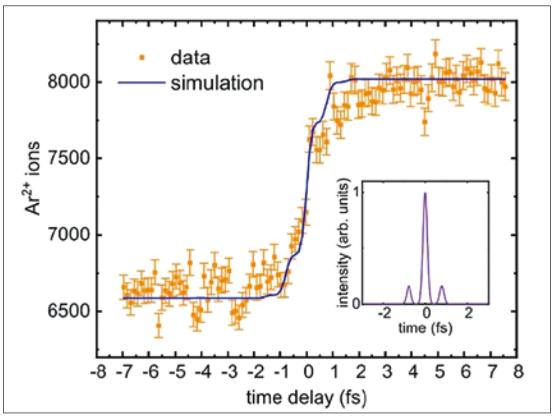


Figure 1: Two-colour APAPS. The generation of Ar^+, as initiated by a broadband attosecond pump pulse with a photon energy around 20 eV, is probed by a second pulse with a central photon energy of 33.5 eV. This is above the second ionisation potential of Ar, thereby producing Ar^{2+}. The Ar^{2+} ion yield increases around zero delay due to the more efficient generation of Ar^{2+} when the probe pulse follows the pump pulse. The inset shows a fit of the attosecond pulse structure.

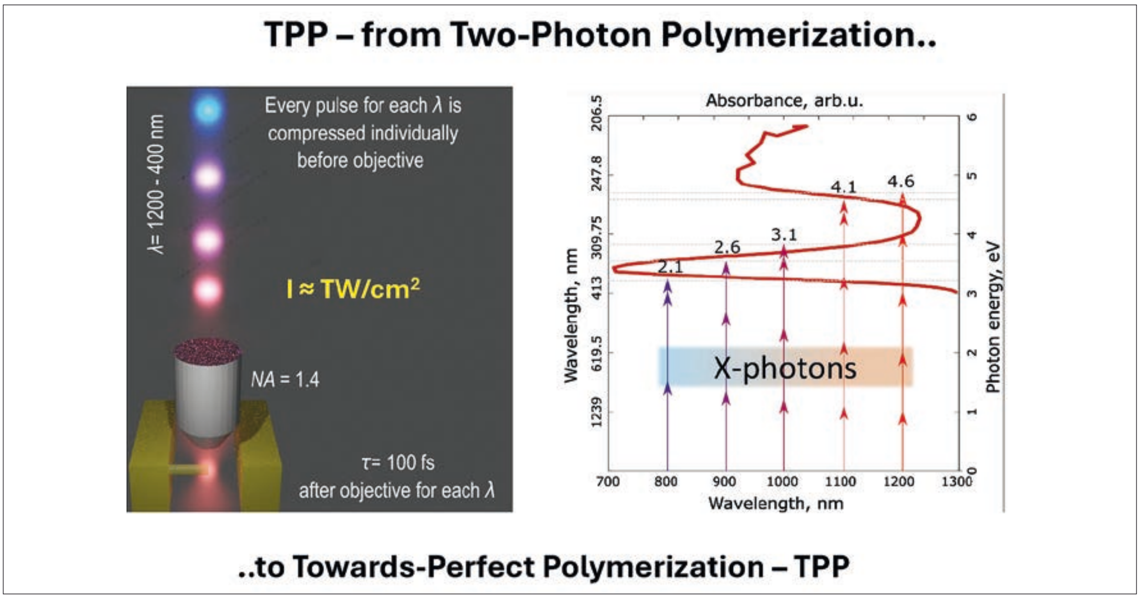
Bernd Schütte (MBI)

[1] S. Li et al., Science 383: 1118 (2024)
[2] M. Kretschmar et al., Sci. Adv. 10: eadk9605 (2024)

X-Photon 3D Polymerisation (VULRC, Lithuania)

Ultrafast lasers, at both short pulse durations and high repetition rates, enable practical, non-linear light-matter interaction for advanced material processing. One of the most successful implementations is two-photon polymerisation (TPP), a high precision optical three-dimensional printing technique, which is already being used commercially as an additive manufacturing tool. Novel laser sources and new material choices offer additional options for the fabrication of functional 3D micro-/nano-devices, but also present challenges in determining the exposure parameters that should be used to deliver the optimal outcome in terms of resolution, throughput, repeatability, cost efficiency, and ease of use.

Modern, wavelength-tunable femtosecond laser sources enable the systematic study of laser direct writing processes, which will help to uncover fundamental details, and provide practical know-how and recommendations for implementation. A recent study revealed that, once a certain intensity of TW/cm^2 is reached at any wavelength, X-nm wavelength enabling an X-photon transition can be applied for well controlled 3D structuring. This finding builds on existing knowledge that a specific, quantised number of photons is needed to realise the material excitation that will trigger a polymerisation reaction, with that number directly related to the laser wavelength and absorption of the material. It was assumed that the polymerisation reaction for



Adapted from E. Skliutas et al., Virtual. Phys. Prototyp. 18(1), e2228324 (2023)

TPP – from two-photon polymerisation to towards-perfect polymerisation

TPP, with two photons, would follow an I^2 scaling law for the light-matter interactions, whereas it is defined by I^x. The initial excitation of the first electrons leads to avalanche ionisation, accompanied by thermal accumulation, which together lead to irreversible photo-modifications.

Exploitation of X-photon excitation for lithography will provide access to various laser wavelengths, thereby extending the spectrum of usable materials, and will eliminate the need for photo-initiators. X-photon high intensity material processing can potentially achieve higher resolution, and could provide more controlled and tailored energy deposition.

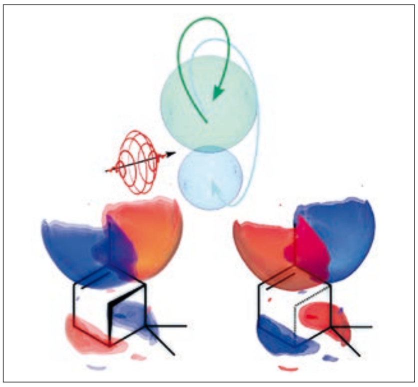
Mangirdas Malinauskas and Saulius Juodkazis (VULRC)

E. Skliutas et al., Virtual. Phys. Prototyp. 18: e2228324 (2023)

Laser-induced electron diffraction in chiral molecules (CELIA, France)

Laser-induced electron diffraction (LIED) is an imaging technique in which a molecule is probed by its own electron [1]. Within a few femtoseconds, a strong laser field removes an electron wavepacket from the molecule, accelerates it and drives it back to its parent ion. The rescattering of the electron wavepacket onto the molecular potential produces a diffraction pattern that encodes the molecular structure with Angstrom spatial resolution, dictated by the de Broglie wavelength of the electron, and with attosecond temporal resolution, dictated by the duration of the electron wavepacket.

At CELIA, Nirit Dudovich's team from the Weizmann Institute of Science (Rehovot, Israel), conducted LIED measurements in chiral molecules, within Laserlab-Europe transnational access. While LIED measurements had so far relied on linearly polarised light, the team used an elliptical laser field to be able to distinguish a chiral molecule (fenchone or alpha-pinene) from its mirror image [2]. The strong field selectively ionised molecules of a given orientation, and drove the electrons along well-defined trajectories. The direction from which an electron recollided with its parent molecule could be controlled by tuning the ellipticity of the field. A velocity-map-imaging spectrometer was used to record the 3D momentum distribution of the diffracted electrons through a tomographic imaging technique, benefiting from the high repetition rate (1 MHz) of the femtosecond laser source.



Adapted from D. Rajak et al., Phys. Rev. X 14, 011015 (2024)

Schematic view of the electron trajectories recolliding from the two ends of a molecule in a strong elliptically polarised laser field (top), and measured forward/backward asymmetry in two opposite enantiomers of a-pinene (bottom)

Depending on the handedness of the molecule, the electrons were found to be preferentially diffracted forwards or backwards along the light propagation axis. This asymmetry, reaching several per cent, varied with the scattering angle of the electron, defining a chiro-sensitive electron-molecule differential cross-section. Different sets of electron trajectories, recolliding from different angles, were identified in the measurements. Interestingly, the results revealed that electrons recolliding from the two ends of an a-pinene molecule were scattered in opposite directions along the light propagation axis, due to their distinct encounters with the chiral potential.

Two decades ago, the collision between electrons and oriented chiral molecules had been predicted to be highly enantio-sensitive [3], but it had not been possible to demonstrate it before now, because of difficulties in controlling the orientation of the chiral molecules with respect to the electron beam. Strong-field ionisation thus offered an unexpected solution to this issue, and now opens up a new path towards resolving ultrafast chiral dynamics with high spatial and temporal resolutions.

Valérie Blanchet, Yann Mairesse and Bernard Pons (CELIA)

[1] K. Amini and J. Biegert, Adv. At. Mol. Opt. Phys. 69: 163 (2020)
[2] D. Rajak et al., Phys. Rev. X 14: 011015 (2024)
[3] A. Busalla et al., Phys. Rev. Lett. 83: 1562 (1999)

Demonstrator experiment of seeded FEL lasing of the COXINEL beamline, driven by a laser plasma accelerator

HZDR/Sylvio Dittrich

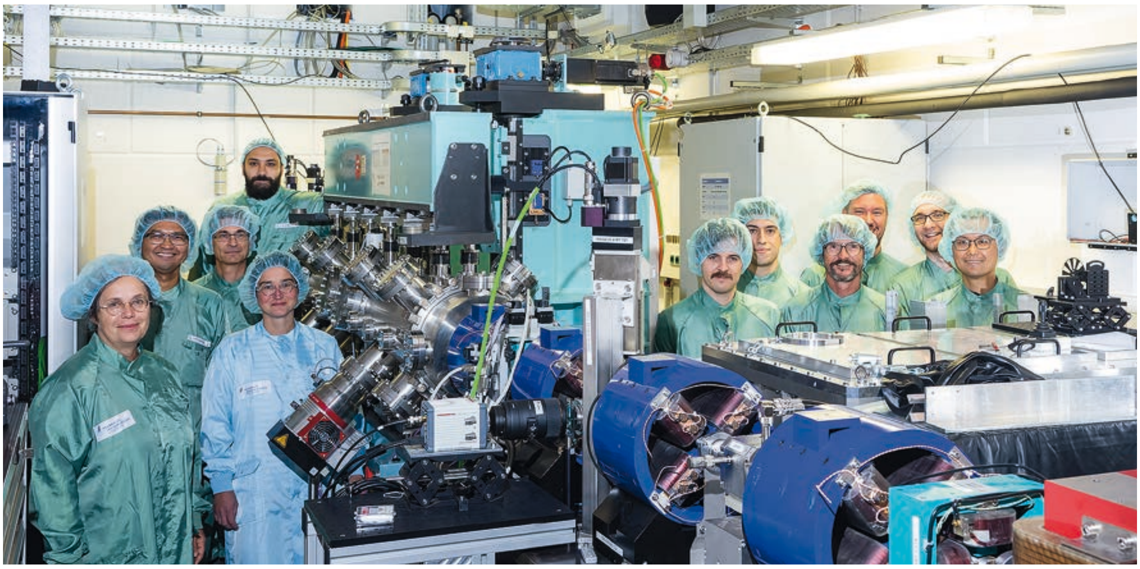


Figure 1: The German-French team, together with colleagues from Synchrotron SOLEIL, LOA, PhLAM and HZDR, succeeded in generating well-controlled FEL light via plasma acceleration. From left to right: Dr Marie-Emanuelle Couprie, Dr Arie Irman, Prof Ulrich Schramm, Dr Marie Labat, Dr Amin Ghaith, Dr Maxwell LaBerge, Dr Driss Oumbarek-Espinos, Dr Alexandre Loulergue, Dr Jurjen Couperus Cabadağ, Patrick Ufer, Dr Yen-Yu Chang).

The invention of the Free-Electron Laser (FEL) – capable of producing high-brilliance coherent radiation, fully tunable from the infrared to the x-ray domains – has opened new scientific avenues for the investigation of matter with atomic resolution and on ultrafast timescales. Progress has been enabled by the continuous improvement of the electron beam quality of conventional linear accelerators. In parallel, the rapid development of laser plasma accelerator (LPA) electron sources has paved the way towards alternative drivers for FELs, and it is envisioned that their use will enable facility size to be downsized by more than one order of magnitude, particularly for short wavelength radiation generation.

Unlike their counterparts, LPAs deploy relativistic laser pulses focused into a plasma to excite micron-scale charge displacement waves that travel in the pulse wake, and utilise the resulting extreme electric fields (the wakefields) for electron acceleration. The first observation of FEL gain driven by an LPA was reported by a group from SIOM (China), lasing at 27 nm in the self-amplified-spontaneous-emission (SASE) regime [1], but the configuration lacked longitudinal coherence. Recently, an international team (Figure 1) has achieved a breakthrough, demonstrating FEL lasing at 270 nm in a seeded configuration [2]. The work, led by Marie-Emmanuelle Couprie, Synchrotron SOLEIL, France, and Ulrich Schramm, HZDR (Helmholtz-Zentrum Dresden-Rossendorf), Germany, was carried out at the 150 TW DRACO laser facility at HZDR, within the framework of the Laserlab-Europe transnational access programme. Success was made possible by combining two key innovations: the COXINEL (Coherent X-ray source Inferred from Electron accelerated by Laser) line, which enabled beam phase-space manipulation, and the stable operation of the HZDR LPA source in a regime of high-charge and low-divergence.

The COXINEL line was designed by Synchrotron SOLEIL (*ERC Advanced Grant, M.E Couprie*). It was first implemented in Laboratoire d'Optique Appliquée (LOA, France), where the LPA electrons were produced by the Salle Jaune laser (*ERC Advanced Grant, V. Malka*). The line features an LPA-optimised beam transport concept [3]. The electron bunches are captured immediately behind the LPA stage with variable high-gradient permanent magnet quadrupoles, to mitigate chromatic emittance growth. Phase-space is then rotated in a magnetic decompression chicane for slice energy spread reduction, followed by chromatic focusing to synchronise the beam focus with the light progress inside an undulator magnet. Over several years, in collaboration with PhLAM (Physique des Lasers Atomes et Molécules, Lille, France), extensive testing and optimisation took place to master the LPA beam transport control [4], and analyse the generation of undulator spontaneous emission [5]. However, as the electron beam quality was insufficient for

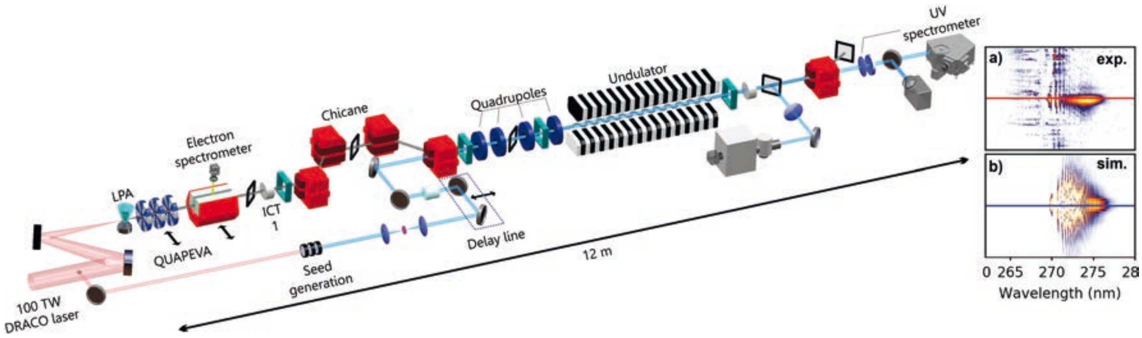


Figure 2: (Left) Schematic of the COXINEL line installed at HZDR. (Right) (a) Measured and (b) simulated spatio-spectral distribution of LPA-based seeded FEL light.

lasing, the COXINEL line was transferred to the DRACO laser facility in October 2021 (Figures 2 and 3), where more intense electron beams had been achieved [6].

The advanced LPA at HZDR relies on a self-truncated, ionisation-induced injection scheme, tailored through beam loading for the generation of very high charge electron bunches with narrow energy bandwidth. In addition, the gas density profile directly at the accelerator exit is shaped to support a plasma lens effect, for beam divergence reduction [7]. The combination of these key ingredients – high charge, small energy spread and low divergence, and thus high spectral charge density – with stable accelerator operation over hours, and even days, was essential for the FEL experiment. A two-week commissioning phase allowed electron beam transport optimisation, undulator radiation characterisation, and seed laser preparation, and the spatio-temporal overlap issue was also solved. Following this, the first seeded FEL light was observed at 270 nm. It was demonstrated that the radiation could be controlled not only by tuning the undulator gap, but also by adjusting the time delay between the electron bunch and the seed laser pulse. This important finding takes advantage of the energy and wavelength chirps of both the electron and the seed laser beams, respectively. Furthermore, pronounced phase-locked interference fringes, resulting from interaction between the seed and FEL pulses, confirm the longitudinal coherence (Figure 2a) [8]. This latter feature highlights the key characteristic of the FEL in the seeded configuration.

Although the results from this experiment represent a major step forward for the advanced accelerator community, there remain challenges to be resolved before the technology is mature enough for practical use. The present experimental benchmarking of FEL codes under LPA conditions will guide the design of future experiments, where gain saturation appears to be in reach for wavelengths down to the extreme ultraviolet range. Pushing further into the x-ray range will, however, require electron beams of much higher quality, at GeV energy level. This grand challenge is currently being addressed through the EuPRAXIA project in Europe [9]. It will require intensive research into the basic physics of LPAs, such as controlled injection and acceleration, as well as into new drive laser technology and plasma targets, in particular to increase the pulse repetition rate.

Reducing the size of FELs in the future could substantially broaden the application areas; for example, they could be used to probe relativistic laser plasmas at so far unreachable plasma density scales in a combined facility.

Marie Labat (Synchrotron SOLEIL), Arie Irman (Helmholtz-Zentrum Dresden-Rossendorf), Marie-Emmanuelle Couprie (Synchrotron SOLEIL), Ulrich Schramm (Helmholtz-Zentrum Dresden-Rossendorf)

[1] W. Wang et al., Nature 595: 516-520 (2021)
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[7] Y.-Y. Chang et al., Phys. Rev. Applied 20: L061001 (2023)
[8] M. Labat et al., New J. Phys. 22: 013051 (2020)
[9] *https://www.eupraxia-project.eu/*

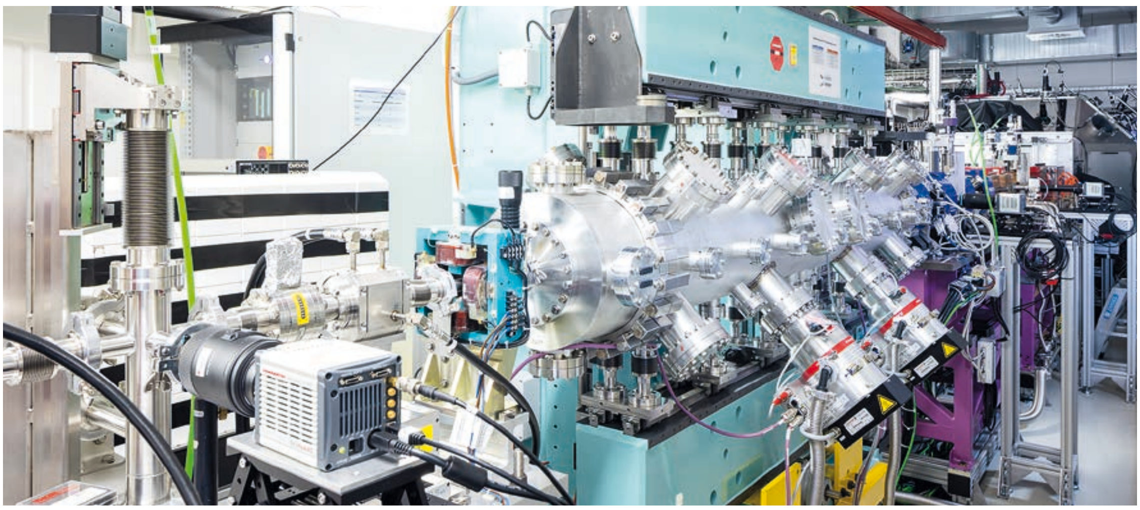

Figure 3: The COXINEL FEL line from SOLEIL converts the electron pulses generated by the high-power laser DRACO at HZDR into light flashes: undulator (foreground); metallic beam chamber for the DRACO laser (background).

ELI’s strategic integration and scientific advancements

Since 1 January 2024 the Extreme Light Infrastructure (ELI ERIC) operates the ELI Beamlines and ELI ALPS Facilities under a unified governance and single management structure. This strategic integration not only streamlines administrative and operational processes but also amplifies the research and innovation activities by facilitating scientific synergies. A key aspect of the integration is the establishment of a single User Office which leads the User Programme aligning processes across the ELI Facilities for a unified user experience and to enhance the quality of user services. The Science Office has successfully launched the 4th User Call in April 2024 with the 5th Call poised to open from 25 September to 29 October 2024. For more details about the User Programme join the annual ELI User Meeting on 26-28 June 2024 in Dolní Břežany, near Prague.

ELI ERIC

ELI ERIC

Recent scientific highlights at ELI include breakthroughs in high-field physics, particularly the inaugural petawatt (PW) laser-driven shots at the SHHG beamline, marking a milestone in high-field interaction studies. The L3 HAPLS laser system is enabling unmatched opportunities in laser plasma acceleration on the ELIMAIA Laser-Plasma Ion Accelerator with the generation of protons, electrons, and X-rays. ELI also launched an initiative developing a technical roadmap outlining the utilisation of the ELI laser systems to support the design, development and delivery of technologies for future laser-driven fusion energy reactors. The initative is supported by the German Ministry of Education and Research and implemented two workshops for the scientific community with more activities foreseen.

EU project RIANA launched: A hub for Nanoscience and Nanotechnology

RIANA (Research Infrastructure Access in Nanoscience & Nanotechnology) has officially been launched on 1 March to offer access to Europe’s leading facilities in nanoscience and nanotechnology that are at the heart of the development of new materials for prosperity and sustainability.

Access to almost 70 infrastructures

The RIANA project provides the user community with a unique platform of 69 infrastructures from 22 European countries, including synchrotron, electron microscopy, laser, ion beam, neutron, clean room, and soft matter research infrastructures as well as high performance computing. Beyond standard user access to single facilities, RIANA offers a single-point access and a particularly strong user support by a network of junior scientists.

RIANA will engage with academic and industrial users via a rolling call system and promote experiments that combine different facilities and techniques. This combination of scientific tools will enable new approaches and an expansion of the user community, paving the way for accelerated innovation based on nanomaterials.

The following Laserlab-Europe infrastructures offer access to laser related techniques: CALT, CELIA, CLF, CLL, CLPU, CLUR, CUSBO, FELIX, FERMI, HiLASE, INFLPR, LENS, LIDYL, LLC, LP3, MUT, and ULF-FORTH.

https://riana-project.eu

How to apply for access

Interested researchers are invited to contact the Laserlab-Europe website at www.laserlab-europe.eu/transnational-access, where they find relevant information about the participating facilities and local contact points as well as details about the submission procedure. Applicants are encouraged to contact any of the facilities directly to obtain additional information and assistance in preparing a proposal.

Proposal submission is done fully electronically, using the Laserlab-Europe Proposal Management System. Your proposal should contain a brief description of the scientific background and rationale of your project, of its objectives and of the added value of the expected results as well as the experimental set-up, methods and diagnostics that will be used.

Incoming proposals will be examined by the infrastructure you have indicated as host institution for technical feasibility and for formal compliance with the EU regulations, and then forwarded to the Access Selection Panel (ASP) of Laserlab-Europe. The ASP sends the proposal to external referees, who will judge the scientific content of the project and report their judgement to the ASP. The ASP will then take a final decision. In case the proposal is accepted, the host institution will instruct the applicant about further procedures.

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