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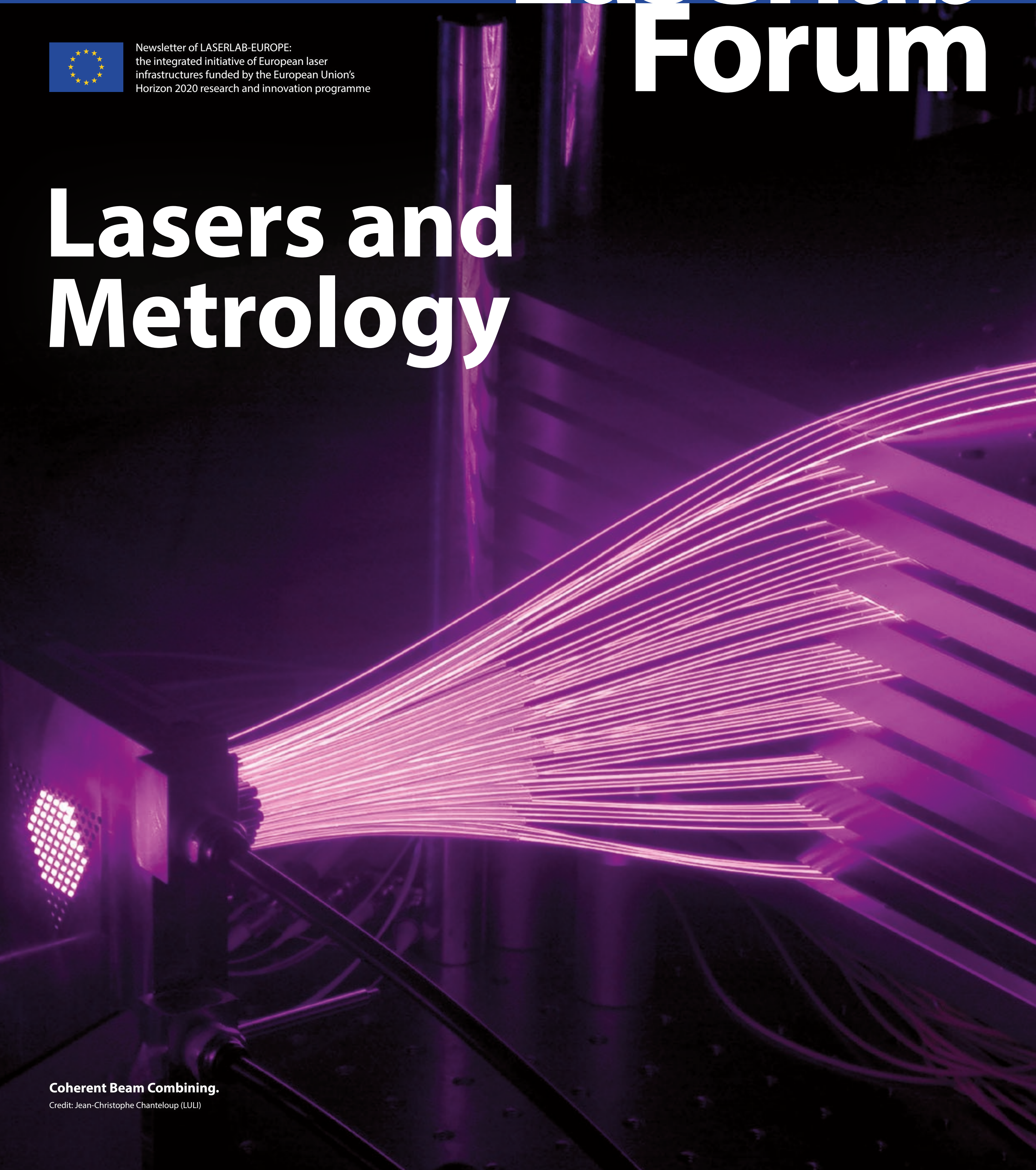
Laserlab Europe

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

Lasers and Metrology



Coherent Beam Combining.
Credit: Jean-Christophe Chanteloup (LULI)

In this Issue

Editorial

Tom Jeltes

Laser metrology is everywhere these days. Any self-respecting handyman owns a pocket laser device to measure distances in the blink of an eye, laser interferometers allowed the revolutionary detection of gravitational waves in 2016, and it seems a matter of time before the most accurate clocks are based on laser metrology.

Metrology is the science of measurement, and lasers have become an indispensable tool for scientists wanting to measure physical quantities to great precision – naturally not the least within Laserlab-Europe. Metrology, however, has a slightly different meaning for our researchers as well: it is also the art of characterising the properties of their lasers and optical components, which is often a prerequisite for performing that other type of metrology – the scientific one.

This issue of Laserlab Forum features a focus section on 'Lasers and Metrology', in which both types of laser metrology are addressed. Strikingly, the input from our French partners is substantial, which might not come as a surprise considering the fact that the history of metrology dates back to the French Revolution, and that the current international system of standards, the Système International, is a French invention.

Coincidentally, the access highlight is also from France – from Saclay, to be more precise. This contribution from our partner LIDYL shows how three-dimensional X-ray images can be constructed with a lensless imaging approach using computer vision algorithms.

Also in this issue, an update of the Romanian pillar of the Extreme Light Infrastructure: ELI – Nuclear Physics, as well as our familiar short descriptions of new ERC Grant projects from Laserlab-Europe researchers. Enjoy!

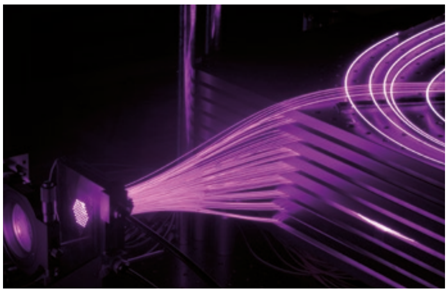
Tom Jeltes

News

New method for combining femtosecond laser beams

Researchers at Laserlab-Europe partner LULI (Paris-Palaiseau) have been able to combine over sixty coherent femtosecond laser beams using fibre amplifiers. The demonstrated technology could theoretically be scaled up to ten thousand fibres, opening the way to producing femtosecond pulses at the Joule level.

Coherent beam combining (CBC) is a technique which involves coherently adding the output beams of several independent amplifiers seeded by a common source. Already, CBC has been used to produce over 10 mJ of output energy per pulse. However, for femtosecond pulses to reach the Joule level and address applications such as particle acceleration, several thousands of fibres need to be combined. In a project with the company Thales, researchers at LULI have now demonstrated a highly scalable architecture using a tiled aperture configuration employing hexagonal stacking of the fibres and their respective collimating microlenses. In addition, an interferometric phase measurement technique is implemented, which allows to determine the phase shifts of all the beams in one single frame acquired from a fast camera and to correct them with a kHz bandwidth feedback loop.



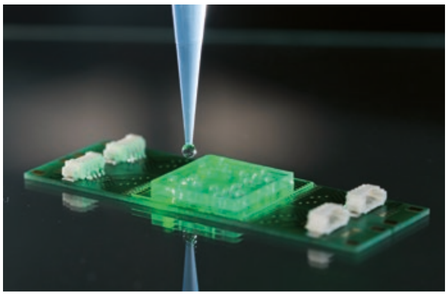
© Jean-Christophe Chanteloup (LULI)

Coherent Beam Combining.

New Research Centre for Infectious Diseases in Jena

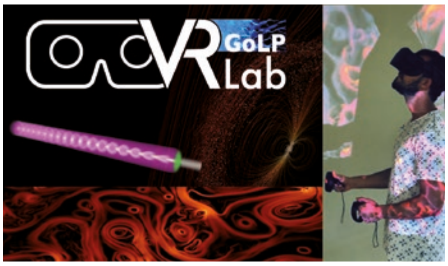
The German government has decided to fund a new Leibniz Centre for Photonics in Infection Research (LPI) in Jena with approximately 150 million euros. The LPI, with involvement of Laserlab-Europe partner Leibniz IPHT and Friedrich Schiller University Jena, will allow good ideas from research to reach patients more quickly.

Light-based, i.e. photonic, methods measure quickly and without contact and contribute to a better understanding of how microbes make people ill, how the body resists and how these processes can be influenced. At LPI, natural scientists, technology developers, physicians and medical technology manufac-



A light-based diagnostic method: a chip researched by a team from Leibniz IPHT and Jena University Hospital for the rapid diagnosis of infectious diseases.

turers will develop light-based technologies for better diagnostics and therapy of infectious diseases in the future. The new research centre bundles the expertise available in Jena in the fields of optics, photonics and infection research and will be open to national and international researchers as well as industrial users.



Virtual reality lab creates plasma experience

Using an innovative combination of images, videos, sounds, and experiences in virtual reality, the GoLP VR Lab from Laserlab-Europe partner IST (Lisbon) transforms the scientific data of their plasma research into a fully interactive artistic experience for the audience.

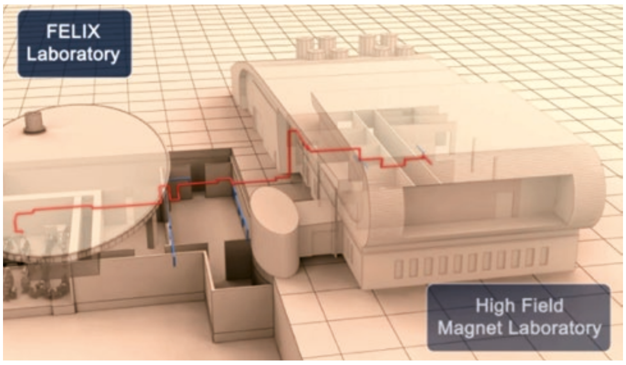
The plasma virtual reality lab is a project realised by Giannandrea Inchingolo and Fábio Cruz, Ph.D. candidates at IST's Group of Lasers and Plasmas (GoLP). From the far astrophysical scenarios to the latest innovations in plasma accelerators, the project creates the possibility of diving into the plasma realm, discovering the physics that governs all these different plasma scenarios. A core part of the GoLP VR Lab is *Turbulence | Voice of Space*, Inchingolo's personal project in which he adapts his personal research in turbulent plasma with the latest media art techniques, in collaboration with Prof. Joseph Paradiso from MIT Media Lab in Boston, and the Virtual Beamline group of ELI Beamlines in Prague.

Since its launching in early 2019, GoLP VR Lab has been exhibited in several national and international events dedicated to outreach and science communication, such as the MIT MediaLab *Beyond the Cradle 2019* and *Ciência 2019*, the Portuguese annual national meeting for Science and Technology, receiving extremely positive feedback from the audience.

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 33 leading organisations in laser-based inter-disciplinary research from 16 countries. 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.

Combined building HFML-FELIX officially opened



The new combined building in Nijmegen.

A combined building of the High Field Magnet Laboratory (HFML) and Laserlab-Europe partner FELIX (Free Electron Lasers for Infrared eXperiments) Laboratory has been officially opened in Nijmegen (The Netherlands) on 8 July 2019 by the Dutch Minister of Education, Culture and Science, Ingrid van Engelshoven.

Uniquely, the facility offers both a static high magnetic field (currently up to 38 Tesla) and intensive (far) infrared light as well as terahertz radiation (0.2 THz – 100 THz) at a single location, allowing an entirely new scientific domain to be entered. With this combination of equipment fundamental questions regarding for example the origin of superconductivity at high temperatures might be answered.

Groundbreaking discoveries have already been made in Nijmegen. Using the high magnetic field at HFML, Konstantin Novoselov and Andre Geim were the first to discover the 2D material graphene. The intense laser light at FELIX plays a crucial role in mapping chemical processes and molecular structures – allowing, among other things, the study of new biomarkers that help physicians track various diseases.

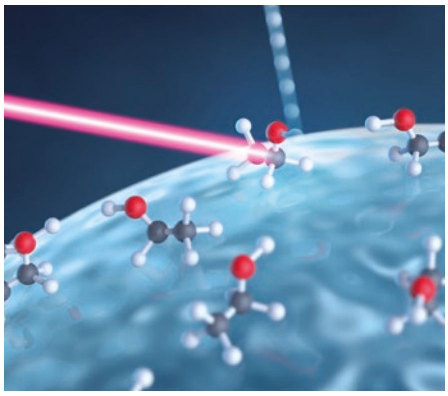
An ultrafast glimpse of the atmosphere's photochemistry

Researchers at German Laserlab-Europe partner MPQ (Garching) and Ludwig-Maximilians Universität have explored the initial consequences of the interaction of light with molecules on the surface of nanoscopic aerosols. Their research has been published in *Nature Communications* (10: 4655, 2019).

Light-induced molecular processes are significantly accelerated when the reactants are absorbed on the surface of nanoparticles in the atmosphere. This phenomenon is crucial for the photochemistry of the atmosphere and thus has an impact on our health and climate.

The researchers have used a new method, called reaction nanoscopy, to characterise the reaction of ethanol with water molecules on the surface of glass nanoparticles under the influence of high-intensity laser light. They irradiated the spherical particles with ultrashort laser pulses, each lasting for a few femtoseconds, and were able to record this ultrashort interaction in three dimensions with nanometer resolution.

In the short term, the results obtained with the new analytical procedure by the laser physicists may provide useful insights, especially in the field of atmospheric chemistry. Eventually, they could lead to a better understanding of reactions on aerosols, and might even point to ways of slowing the rate or mitigating the effects of climate change.



ERC Starting Grants

Each year, a significant number of Laserlab-Europe researchers are awarded prestigious personal grants by the European Research Council. Here, we highlight five recently granted ERC Starting Grant projects, meant for young researchers who completed their PhD between two and seven years ago. The grants, worth up to 1.5 million euros for a period of five years, go to Dmitri Efetov (ICFO, Spain), Matteo Lucchini (POLIMI, Italy), Guillaume Salomon (MPQ, Germany), Andreas Ehn and Mikkel Brydegaard (both LLC, Sweden).

Dmitri Efetov (ICFO): Superconductivity in 'magic angle' graphene


© ICFO

The discovery of a material that is superconducting at room temperature and atmospheric pressure would cause a major technological revolution. Motivated by the fact that so-called 'magic angle' graphene bilayers exhibit a phase diagram which looks like that of high-temperature superconductors, Dmitri Efetov will use his ERC Starting Grant to investigate the behaviour of this type of graphene in search of deeper understanding of the physics of superconductivity. He intends to engineer new structures of magic angle graphene and will design experimental schemes to perform a holistic study of the superconducting properties of this novel compound. The overall goal will be to reveal symmetries as well as the macroscopic phase, spin state and excitation spectrum of the material.

Matteo Lucchini (POLIMI): Attosecond dynamics in two-dimensional materials

Two-dimensional (2D) materials might become the building blocks of the electronics of the future. Many of the exotic physical, electronic, and chemical properties of 2D materials that arise from electron confinement in two directions, however, are not understood, and no suitable tools exist to study the ultrafast processes unfolding during light-matter interaction. In his ERC Starting Grant project, Matteo Lucchini therefore aims to explore electron, exciton, and spin dynamics on a sub-femtosecond timescale by developing a pump-probe beamline for transient absorption and reflectivity measurements based on arbitrarily polarised attosecond pulses in a two-foci geometry.

Andreas Ehn (LLC): Filming cold plasmas with lasers

In so-called non-thermal or 'cold' plasmas, such as can be found in fluorescent light tubes, the energy of the free electrons is much higher than that of the plasma gas as a whole. This energy can therefore be used to create new substances in an efficient way, but the formation of cold plasmas, and their interaction with their surroundings is

extremely fast and unpredictable. In his ERC Starting Grant project, Andreas Ehn, will extend the capabilities of the laser-based 'world's fastest camera' recently developed at LLC, capable of capturing five trillion images per second, to study air plasmas, plasma conversion of CH_2/CH_4 gas mixtures, and plasma-assisted combustion.

Mikkel Brydegaard (LLC): Detecting insects with lasers

To be able to manage insects, both those which are considered pests and those which are wanted as pollinators, one has to understand their ecology: which species can be found in a particular area, and how many, and what are their daily rhythms and lifecycles? With his ERC Starting Grant, Mikkel Brydegaard will develop a laser tool to determine insect's wing thickness on a nanometre scale from a distance of several kilometres, using the wings as a 'laser mirror'. The main aim of the tool is to be able to identify different species of insects in flight. Currently, different species of mosquitos are identified by DNA analysis, but Brydegaard and his colleagues have already shown that wing thickness can in principle be used to distinguish closely related mosquito species.

Guillaume Salomon (MPQ): Searching for fractional quantum states


© MPQ

A spectacular phenomenon in quantum many-body systems is the emergence of non-local quasiparticles with fractional quantum numbers and so-called anyonic statistics. The search for such fractionalised quantum states is especially motivated by the promise it holds for fault-tolerant quantum computation. With his ERC Starting Grant, Guillaume Salomon will build a novel strontium quantum gas microscope to study both fractional quantum Hall states and highly frustrated magnets - two systems predicted to display fractional quantum states because of their shared property of massive ground state degeneracy.

Lasers and Metrology

Lasers are outstanding measurement tools, and as such intimately linked with modern metrology – the 'science of measurement'. But for many laser scientists, lasers are more than just tools – they are also the object of study. This focus section shows how within Laserlab-Europe both metrology *with* and *of* lasers is being conducted, ranging from the use of frequency comb lasers to measure fundamental constants to characterisation of optical components, identification of the laser induced damage threshold of 3D microstructures, and several methods to measure the properties of laser pulses in detail.

Optical frequency metrology with frequency comb lasers (LaserLaB Amsterdam)

Over the past two decades, optical frequency comb lasers have revolutionised the way in which coherent light is produced and characterised, from the far infrared to the extreme ultraviolet (XUV). LaserLaB Amsterdam boasts a number of frequency comb laser systems, which form the core of experiments which measure the properties of calculable atoms and molecules with very high precision, thus enabling tests of the predictions of fundamental physical law at their very limits.

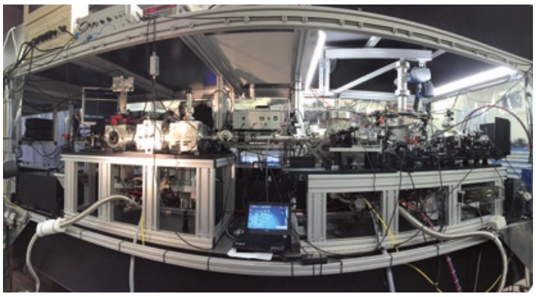
As a result of many years of development, including support from Laserlab-Europe through Joint Research Activities and access, optical excitation of atoms and molecules with coherent narrowband sources has been successfully applied to determine the structure and properties of systems such as helium atoms, hydrogen molecules, and their ionised counterparts. LaserLaB Amsterdam uses a number of advanced techniques to cool, store and manipulate these species under well controlled conditions based on laser cooling and trapping, ion traps, and the world's first molecular fountain.

With these methods, a spectral resolution in excess of 1 part in 10^{12} is achievable, although several challenges need to be overcome. For example, leveraging the high potential precision requires optical frequency measurements achieving a similar level of accuracy. This is precisely what frequency combs provide: direct optical frequency measurements (at hundreds of terahertz), utilising the frequency comb as an optical ruler which is stabilised to an atomic clock for accuracy. This has enabled optical frequency measurements in helium and in neutral and ionised molecular hydrogen with a relative uncertainty down to 1 part in 10^{12}, which have been used to put fundamental physics theories to the test, and to constrain possible 'Fifth forces' of nature.

Another challenge is presented by the atoms and molecules themselves, which often have transitions of great physical interest located in the VUV and XUV wavelength range. LaserLaB Amsterdam has developed a scheme which takes advantage of the short, intense pulses of the frequency comb laser, and the exquisite control it offers over the optical phase, to up-convert these pulses and use them to directly excite atomic and molecular transitions with a new form of differential Ramsey spectroscopy in the hitherto difficult to access VUV and XUV domain.

Last but not least, LaserLaB Amsterdam has been developing methods to distribute the high optical frequency accuracy and stability of its laser sources to other facilities through telecom optical fibre, and also to provide access to even more accurate atomic clock reference signals from national metrology institutes through the optical fibre network.

Jeroen Koelemeij, Hendrick Bethlem, Wim Ubachs, Kjeld Eikema (LaserLaB Amsterdam)



Setup at LaserLaB Amsterdam for high-precision Ramsey-comb spectroscopy using light produced by High-Harmonic Generation.

L.S. Dreissen et al., Phys. Rev. Lett. 123: 143001, 2019

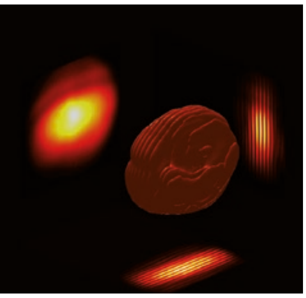
Ultrashort pulse metrology using TERMITES and INSIGHT (LIDYL, France)

Full spatio-temporal characterisation of ultrashort laser pulses is difficult because the beam's spatial properties are frequency dependent. Two new measurement techniques, TERMITES and INSIGHT, have been developed at the Laboratoire Interactions, Dynamique et Lasers (LIDYL, Paris-Saclay) to overcome this problem and were recently used to fully characterise the powerful femtosecond laser BELLA at Lawrence Berkeley National Laboratory (USA).

Traditional characterisation routines for ultrashort lasers generally combine accurate determination of the temporal pulse profile with advanced diagnostics to measure the spatial properties, such as wavefront sensors. These routines, however, are totally blind to chromatism, i.e. a frequency dependence of the beam's spatial properties, which can easily arise in ultrashort laser beams – as in any broadband light source. They therefore omit some crucial properties of these advanced light sources.

At LIDYL, two new characterisation techniques, TERMITES and INSIGHT, have been developed in the past five years to address this issue in a relatively straightforward way. So far, these techniques have been applied to more than fifteen laser sources, where they have systematically revealed undetected features. They have in particular provided the full spatio-temporal characterisation of one of the most powerful femtosecond lasers in operation to date, the BELLA laser at LBNL (USA).

One of the major difficulties of this advanced metrology of ultrashort lasers is that one needs to measure information in a 3D space (two spatial coordinates across the



3D representation of the E-field of a 100 TW-25fs laser beam.

laser beam, and time or frequency), while available light sensors are still mostly two-dimensional. Both TERMITES and INSIGHT solve this issue by using spatially-resolved Fourier-Transform spectroscopy to obtain spectrally-resolved information at each pixel of a 2D camera.

In TERMITES, this approach is used on collimated beams to compare, in the spectral domain, each point of the test beam to a reference beam, which is created by spatially expanding a small portion of the test beam. In INSIGHT, it is used on a focused beam to measure the frequency-resolved spatial intensity profile of the beam in different planes along the propagation direction. An iterative phase-retrieval algorithm is then applied separately at each frequency to these sets of multiple beam profiles, to determine the spectrally-resolved beam wavefront. With both techniques, after an additional temporal measurement at a single point of the beam for phase stitching along the frequency axis, the laser field is totally reconstructed, either in space-time or space-frequency, and can then be numerically propagated in any plane.

Fabien Quéré (LIDYL)

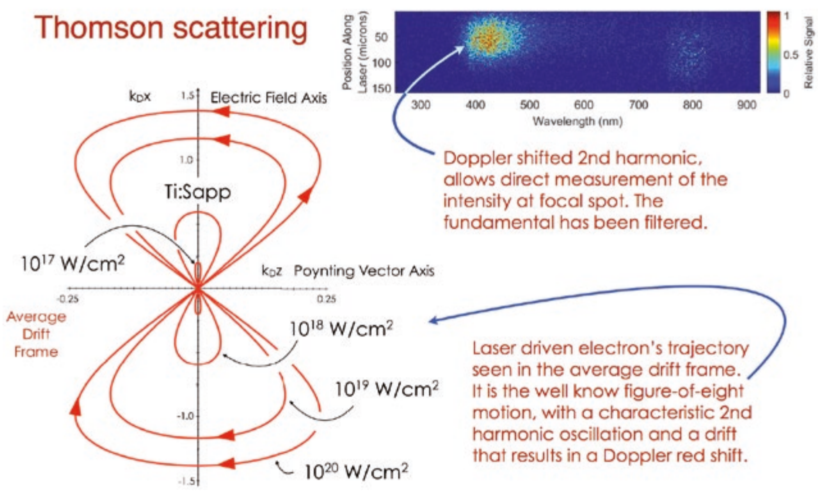
A. Jeandet et al., J. Phys. Photonics 1: 035001, 2019

In-situ focal spot metrology (CLPU, Spain)

In many labs, laser pulses reach relativistic intensities today, precluding direct measurements of the focal spot with detectors because these will be damaged. At the Salamanca Pulsed Lasers Center (CLPU) a new method has now been tested, which allows direct measurement of the focal spot using Thomson radiation from free electrons present in the beamline.

At relativistic intensities (above 10^{18} W/cm^2) it is impossible to place any detector just at the focus because it is going to be destroyed at each laser shot. So all the ways to measure the focal spot are based on indirect measurement, at full power, or extrapolations of the low power measurements; in either situation the measurement is indirect.

Recent experiments performed with the CLPU's VEGA laser, in collaboration with the universities of Maryland and Alberta, show a direct way to measure relativistic intensities at focus. The underlying idea is very simple: at such intensities all atoms are ionised and only free electrons and ions remain, which can be used as detectors. Even at 10^{-6} mb, the standard pressure in many experiments with petawatt lasers, there are a few atoms remaining in the focal volume. Moreover, the introduction of some extra gas (N_2) at levels of 10^{-4} mb does not modify the shape of the focal spot.



At relativistic intensities, ionised electrons oscillate due to the laser fields and radiate due to the relativistic behaviour in higher harmonics of the laser frequency, a process called Thomson scattering. Because the electrons move along the direction of laser propagation they experience a strong Doppler red shift. All this radiation is strongly linked to the laser intensity, so Thomson radiation is a valuable tool to measure the focal spot intensity in-situ.

As intensity increases electrons become too relativistic, rendering the measurement a bit too complicated. However, at the ultrarelativistic limit ($I>10^{24}$ W/cm^2), where not only the electrons but also the protons are moving relativistically, the method can be applied again using the Thomson radiation pattern coming from the protons/ions. Therefore, this method is not only useful at present, using radiation scattering from laser-driven electrons, but also in the future, when scattering from laser-driven protons can be employed. To our knowledge, this is the first tool ever prepared to measure the ultrarelativistic laser frontier in-situ, suitable for the foreseen exawatt laser projects.

Luis Roso (CLPU)

C.Z. He et al., Optics Express 27: 30020, 2019

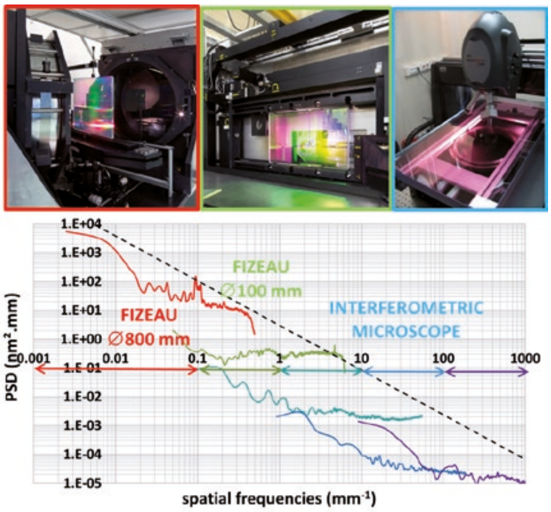
Large optics metrology for the LMJ facility (CESTA, France)

The high power laser facility Laser MégaJoule (LMJ) near Bordeaux employs thousands of meter-sized optical components, which all have to fulfill strict quality requirements. The optical metrology laboratory of the Centre d'Etudes Scientifiques et Techniques d'Aquitaine (CEA-CESTA) has developed a wide set of metrology instruments specific to these large optics.

At the time of writing, LMJ is operating 48 laser beams arranged in 6 bundles. Each 400x400 mm^2 beam can typically provide 3.5 kJ in a 3 ns pulse at 351 nm. LMJ is designed to accommodate 176 such beams. Each beam needs around 40 large optical components (up to 800x400 mm^2): laser glass amplifier slabs, polarisers, spatial filtering lenses, frequency doubling/tripling KDP crystals, dielectric mirrors, gratings, vacuum windows, phase plates, etc. This adds up to thousands of meter-class optics that need to be perfectly qualified.

These components are manufactured all around the world. In order to make sure they fulfill our requirements once equipped on the laser beams and to ensure smooth operations between our different vendors, we have to rely on an undisputable metrology. In the early stages of the project, an optical metrology laboratory was created by the French Alternative Energies and Atom Energy Commission (CEA) to help accomplish all the steps of the construction of this laser.

Over the past two decades, we have developed, qualified and operated a wide set of instruments which enables us to monitor a high standard laser component production flow. These instruments are unique and specific to the size of the optics we want to control.



The three instruments used at CEA-CESTA to control the whole spatial frequency spectrum: Ø 800 mm and Ø 100 mm Fizeau interferometers and interferometric microscope. The chart below shows typical power spectral density (PSD) measurements to illustrate sensitivities and spatial frequency ranges of these instruments.

We usually divide our measurements into four fields of expertise: surface imperfection inspection, photometry, laser induced damage measurement and wavefront measurement. They monitor the main specifications at all steps of an industrial manufacturing process able to produce hundreds of large optics a year. More details can be found in the reference.

Stéphane Bouillet (on behalf of the optical metrology team, CEA-CESTA)

S. Bouillet et al., J. Opt. Soc. Am. A 36: C95, 2019

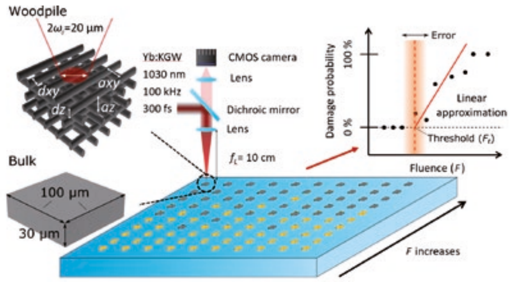
Laser-induced damage threshold metrology of 3D microstructures (VULRC, Lithuania)

Three-dimensional microstructures are already widely used as micro-optics, but for applications at high light intensities, detailed knowledge is required of their laser induced damage threshold. At the Vilnius University Laser Research Center (VULRC) the damage threshold of bulk and woodpile structures of various materials has recently been measured in detail for the first time.

Two-photon polymerisation (TPP), also known as multi-photon lithography, has been established as a precision 3D printing technique allowing rapid fabrication of micro and nano-scale 3D objects. One of the key areas of the technique is the production of micro-optics. While they are already widely used for imaging and spatial light modulation, in order to implement these components also in applications where high light intensities (>GW/cm²) are used (non-linear microscopy, optical tweezing, materials processing), it is important to evaluate their laser-induced damage threshold (LIDT). Some preliminary studies have been carried out in this direction already, but these either used thin films, which are structurally completely different to TPP made objects, gave only qualitative guidelines, or had low practical value.

Therefore, TPP microstructures fabricated using different polymers and writing schemes were tested at VULRC to uncover trends in LIDT values. The tests were performed using the ISO S-on-1 method with femtosecond laser pulse trains. This method delivered statistically determined LIDT values, as well as damage morphologies.

A representation of a typical LIDT experiment is shown in the figure. TPP microstructures are exposed to the focused laser beam one by one. Each row of the 10 x 10 microstructure arrays is exposed to a different laser fluence for one minute. After all microstructures are irradiated, the sample is examined by scanning electron and optical microscopies to evaluate which microstructures are damaged and which ones are not. This allows statistically reliable evaluation of the damage threshold of TPP-made objects.



Schematics of a LIDT measurement. A 10 x 10 array of either bulks or woodpiles is exposed to 1030 nm, 100 kHz, 300 fs laser radiation. Both woodpiles and bulks were 100 µm x 100 µm x 30 µm in size, with the woodpile being arranged in fcc geometry. Each woodpile was also characterised by line width dxy, distance between them axy and period az. Fluence was changed from line to line, from no damage to all structures being damaged. This allowed to plot damage probability as a function of fluence and a linear approximation was then used to determine its value.

Both bulk and woodpile structures were tested in this study. It was shown that the laser-induced damage threshold severely depends on the material (organic *vs* hybrid) and its composition (photosensitised vs without photoinitiator), with hybrid organic-inorganic photopolymers clearly outperforming the rest of the materials tested. The best performing 3D laser lithography made structure in this study was bulk made out of SZ2080 without photoinitiator with a LIDT value of 169 mJ/cm².

Linas Jonušauskas (VULRC)

A. Butkutė et al., Optics Letters, ID: 378915, 2019

At-wavelength metrology of EUV and X-ray optics (LOA, France)

At the Laboratoire d'Optique Appliquée (LOA, Paris-Palaiseau) metrology beamlines have been developed to test optical components for EUV and X-ray radiation. The equipment is 'at-wavelength', meaning that EUV or X-ray radiation is used to validate EUV or X-ray optical components, respectively.

Optical metrology is probably the most crucial step in optics fabrication; opticians tend to say that they are able to correct any defects they can measure. This might be true for visible optics, but metrology has always been a strong limiting factor for EUV ($\lambda < 40$ nm typically) and X-ray optics ($\lambda < 0.1$ nm typically). Here, optical metrology, i.e. using visible light, is not a viable solution considering the current and future requirements of EUV to X-ray optics for EUV lithography, spatial telescopes, synchrotrons and free-electron lasers. Therefore, a new paradigm is needed.

For about 15 years, we have been working at LOA in close collaboration with French manufacturer Imagine Optic to develop compact at-wavelength metrology beamlines that can be transferred to EUV and X-ray optics companies. In these beamlines, non-linear interaction of an intense, femtosecond laser with noble gas produces a high harmonic beam that is highly coherent, collimated, and – under specific conditions – diffraction-limited and thus perfectly adapted to perform at-wavelength EUV and X-ray metrology of optical components.

The beamline for X-ray/EUV metrology at LOA. The 5 kHz, 3 mJ, 30 fs Ti:Sa laser is shaped and focused in the black box on the right. The small cylindrical chamber just behind contains the gas cell for high harmonic generation, the middle chamber holds a spectrometer while EUV optics are tested in the rectangular, versatile and highly stable chamber. An EUV wavefront sensor is attached to the chamber (left part) as a key tool for optics metrology.

The beamline is equipped with an EUV spatial filter used to improve the high harmonic wavefront up to the required quality. Generally, the final wavefront reaches λ /50 rms with λ ≈ 30 nm, and recently we are pushing the performances to reach λ /100 rms. This corresponds to a wavefront of λ /1,000 rms to λ /2,000 rms when compared to the classical optical wavelength of 632.8 nm.

Metrology is performed using two wavefront sensors (one of low numerical aperture and one of high numerical aperture) developed by Imagine Optic, in collaboration with LOA and SOLEIL. So far, several optical components have been tested: from flat, spherical and toroidal mirrors to complex optics like Schwarzschild.

The combination of an achromatic sensor and high harmonic beamline also allows testing of attosecond mirrors. In addition, the beamline is used for research and development of EUV wavefront sensors, and the high degree of coherence of the beamline could be employed to quantify the surface roughness as well.

Today, LOA is exploring solutions to push the wavelengths towards harder X-rays and to transfer the concept of this beamline to manufacturers of EUV and X-ray optics for the benefit of end-users.

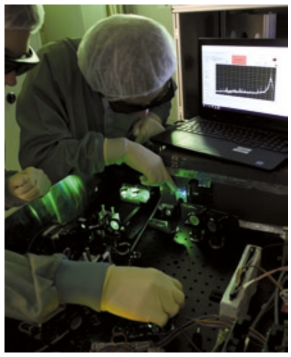
Philippe Zeitoun (LOA)

P. Zeitoun et al., Proc. SPIE 10761: 107610G, 2018

Measuring the influence of the temporal profile of laser pulses during target interactions (GSI, Germany)

Ionisation of a target by laser light does not necessarily occur at the peak of the laser pulse. Therefore, precise knowledge of the temporal structure of the pulse is necessary to correctly interpret the experimental data created during the interaction of high-energy laser pulses with targets. For this reason, at the PHELIX facility of GSI Darmstadt new devices have been developed to characterise the temporal profile of such laser pulses, as well as to obtain information on the evolution of the target.

The standard diagnostic tool for high dynamic range temporal laser pulse characterisation is the cross-correlation technique. Unfortunately, the range in time and intensity necessary to characterise the newest high-temporal-contrast laser systems correctly has increased dramatically. At the PHELIX facility, however, a new device based on the cross-correlation concept shows that this technique can still fulfil today's requirements. Foremost, we demonstrated that a variation of the geometry used for the interaction of the correlating beams reduces efficiently the signal noise. In addition, our calculations show that the dynamic intensity range of a cross-correlator increases with the interaction angle. In our realisation, the detection noise background was observed at 3.7×10^{-14} below the pulse peak intensity [1].



Alignment of the high dynamic range autocorrelator developed at PHELIX.

Complementary information on the target state (temperature, plasma scale length) can be obtained by time-resolved measurements and analysis of the back-reflected and transmitted light pulse after the interaction. For this purpose, we have developed a FROG pulse measurement device with a dynamic range large enough to probe the target state, including the last moments of the rising slope of the laser pulse. Such a device can give a quite precise measurement of the plasma expansion velocity, which is directly connected to the plasma temperature, while the pulse evolution at later times, closer to the intensity maximum, carries information on the plasma scale length. For thin targets, which can transmit a fraction of the laser pulse, a temporal analysis using Fourier-transform spectral interferometry delivers other insights about the pulse intensity in the relativistic regime and the femtosecond electron dynamics after excitation by a high-intensity laser [2].

In our work, the laser is used in combination with very precise characterisation devices to explore the ultrafast dynamics of petawatt laser pulses with matter, understanding of which is mandatory for efficient applications like hadron acceleration or laser-based X-ray generation.

Vincent Bagnoud, Johannes Hornung, Victor Schanz (GSI)

[1] V. A. Schanz et al., Optics Express 25: 9252, 2017
[2] V. Bagnoud et al., Phys. Rev. Lett. 118: 255003, 2017

All-optical, all-solid-state measurement of the waveform of ultrashort laser pulses (LLC, Sweden)

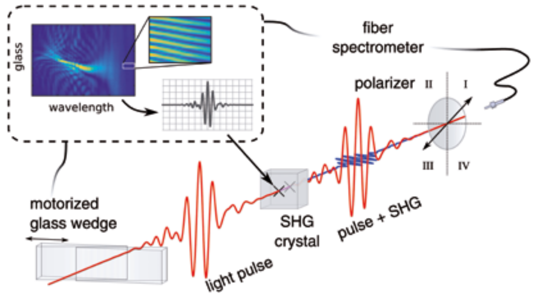
A new all-optical method for measuring the complete field of a light pulse *in situ*, including its absolute phase, has been developed by teams from Sweden's Lund Laser Centre (LLC), Sphere Ultrafast Photonics (Porto, Portugal) and the University of Porto. This new method, published in the journal Optics Letters, shows promise for important applications of few-cycle laser pulses where knowledge of the absolute field of light is paramount, from light-controlled electronics in matter to high-harmonic generation and attosecond science.

Several techniques have been developed that provide access to the spectral phase of ultrashort laser pulses, yet lack information about the absolute electric field of light, i.e., the exact position of the carrier electric field within the laser pulse envelope, also known as the carrier-envelope phase (CEP). Even though there are presently several techniques capable of measuring the full electric field of light, they involve measuring photoelectrons or extreme-ultraviolet radiation under vacuum, and there is a limited choice of where the light field can actually be measured in space.

The new method devised by teams from LLC, Sphere Ultrafast Photonics and the University of Porto, is based on the dispersion scan (d-scan) technique, itself a new method for the measurement and compression of ultrashort light pulses. Of all pulse characterisation techniques, d-scan has the simplest optical setup, devoid of optical delays, beam splitting or recombination, and only requires measuring the spectrum of a nonlinear optical process produced by the light pulse (such as second-harmonic generation) as a function of dispersion applied to the same pulse. The resulting two-dimensional plot, or d-scan trace, enables retrieving the spectral phase of the pulses using a numerical algorithm.

By incorporating the CEP information contained in the d-scan trace directly in the pulse reconstruction algorithm, the teams managed to measure the complete electric field of a light pulse, including its absolute CEP *in situ*, using a purely optical and fully inline setup based only on second-harmonic generation in a standard nonlinear optical crystal. The technique was demonstrated for the case of a hollow-core fiber compressor, which is representative of state-of-the art systems currently used for high-harmonic generation and few-cycle electron acceleration experiments. This new technique could help closing the gap between emerging light-field-driven petahertz optoelectronics and existing waveform characterisation techniques, by enabling all-solid-state measurement of the driving optical waveforms on target.

Helder Crespo (University of Porto), Miguel Miranda and Cord Arnold (LLC)



Concept and simplified schematic of the experimental setup. The pulses are negatively chirped with chirped mirrors (not shown) and go through glass wedges placed on a motorised stage. The pulses are focused on a thin second-harmonic crystal followed by a polariser. The inset shows a typical d-scan trace (second-harmonic signal as a function of glass insertion), a zoom of the trace in the spectral interference region, and the corresponding reconstructed absolute optical field at the entrance face of the crystal. Image taken from Miranda et al. (2019).

M. Miranda et al., Optics Letters 44: 191-194, 2019

Serving 15 years as guardian of excellence

With the beginning of the new funding period of Laserlab-Europe, now in its fifth edition, Prof. Wolfgang Demtröder has retired as Chair of the Access Selection Panel. During 16 years, since the start of Laserlab-Europe, he has been a key person in the selection of the most relevant and interesting research projects to be carried out in Laserlab facilities.

Wolfgang Demtröder (on the left), Chair of the external Access Selection Panel, here together with Didier Normand, who retired earlier this year after long service as Chair of the internal Access Board.

Wolfgang Demtröder, born 1931, obtained his PhD in Physics in Bonn in 1961 with the Nobel laureate Wolfgang Paul and was a Professor of Physics at the Technische Universität Kaiserslautern from 1970 until 1999. During this time he turned the University of Kaiserslautern into an internationally recognized centre for laser technology and laser spectroscopy. Wolfgang Demtröder himself became famous for his fundamental work on high resolution spectroscopy, in particular his contributions to Doppler-free spectroscopy. His textbook "Laser Spectroscopy", which is the main source for advanced courses on laser spectroscopy in Germany and many other countries, covers the basic principles as well as the most recent developments in the field.

As Chair of the external Access Selection Panel, and with a pool of more than 200 referees, experts in the different fields encompassed by the Laserlab-Europe infrastructures, he took care of more than 100 proposals per year. He always ensured a fair and rapid refereeing process. Whenever referees did not respond in time or when their judgements failed to agree, and also contacting new referees could not ensure an evaluation result within a reasonable time, he evaluated the proposals himself. So vast is his knowledge and so fresh his enthusiasm for lasers.

He showed a remarkable sense of duty and his deputies had to substitute him only in extreme circumstances. His commitment to Laserlab-Europe was exemplary and will certainly not be easy to match. His work and attitude is a reference for his successors.

On behalf of all users of Laserlab-Europe, the User Representatives want to express their gratitude for his essential contributions to the success and excellence of Laserlab-Europe and his continuing commitment, and wish him the very best for the years to come.

Thank you Professor Demtröder!

Laserlab-Europe User Representatives

Creating 3D images with X-ray flashes using computer vision

Lensless microscopy with X-rays, or coherent diffractive imaging, is a promising approach in imaging. While two-dimensional images can already be created quickly and efficiently, 3D images are still a challenge. In a recent Transnational Access project performed at French Laserlab partner LIDYL, an international team made up of researchers from Hannover, Hamburg, Lisbon and Paris-Saclay has now demonstrated a new imaging technique that enables reconstruction of a three-dimensional image based on a single acquisition, by combining computer vision and lensless imaging algorithms. The results have been published in Nature Photonics.

At a nanometre scale, the ability to gain insights into the 3D properties of artificial or biological systems is often critical. This information is, however, difficult to retrieve as most techniques provide only two-dimensional projections along the imaging axis. Nowadays, intense ultrashort XUV and X-ray pulses allow realising nanometre scale studies and ultrafast time-resolved 2D movies. Unfortunately, these existing methods are not easily extended to single shot 3D images. As a rule, a three-dimensional image of an object is generated mathematically from hundreds of individual images. This means a high expenditure of time, large amounts of data and high radiation sums.

In the framework of the FET Open project VOXEL, we have now succeeded in significantly accelerating this process by developing a method in which two images of an object can be taken with a single ultrafast acquisition from two different viewing directions, which are then combined to form a spatial image - similar to how the human brain forms a stereo image from the two slightly different images of the two eyes. The method of computer-aided spatial vision is already established in the field of machine vision and robotics. Here it is used for the first time in the field of imaging with X-rays.

This first demonstration uses two XUV coherent beams based on high harmonic generation which are focused on a 3D nanoscale sample. To generate the two sub-beams, we insert a grazing incidence prism between the off-axis parabola and the sample. Two silicon mirrors are adjusted such that the two beam foci overlap on the sample, with a controllable angle. Moreover, the setup enables finetuning of the time delay between the two pulses, and can alternatively be used to perform femtosecond time-resolved X-ray-pump/X-ray-probe experiments.

The two beams are diffracted by the sample and the far field patterns are recorded simultaneously on a single X-ray CCD camera. A typical set of stereo diffraction patterns set at an angle of 19° is shown in Fig. 1. They are slightly different, which reflects the different observation angles. The slight overlap between the two diffraction patterns does not affect the data. Indeed, in our case, the maximal useful diffraction angle is limited by the signal-to-noise ratio. The number of useful diffracted photons on each diffraction pattern is roughly equivalent (few 10^7 photons per shot). Each diffraction pattern is isolated and inverted independently using a HIO "difference map" algorithm.

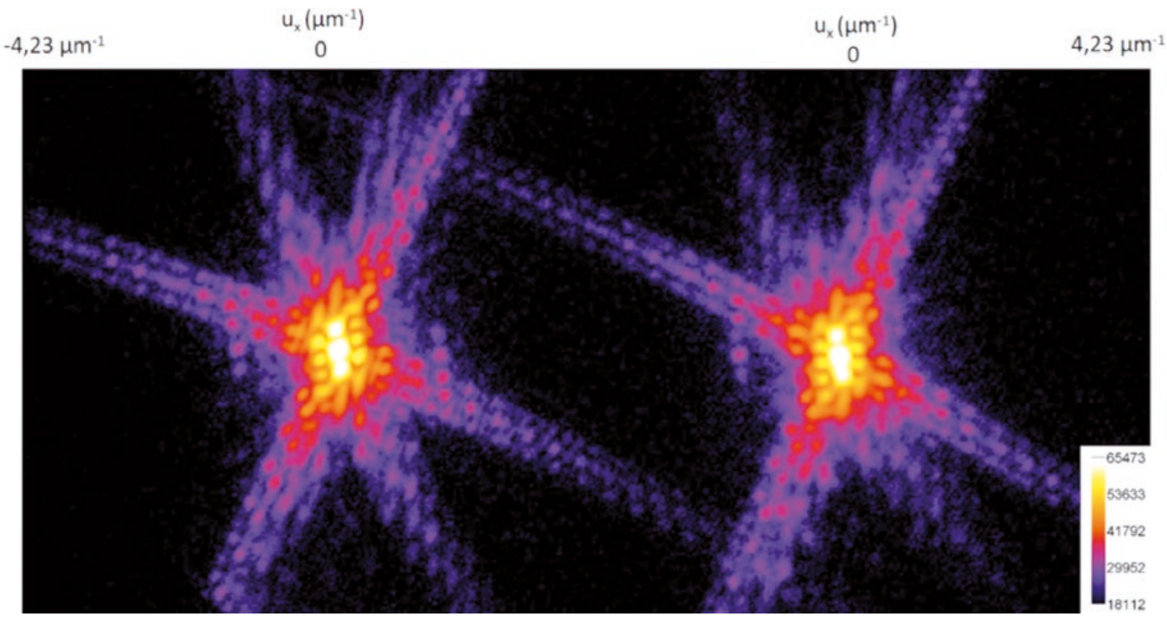


Figure 1: *Dual diffraction patterns, recorded simultaneously on a single XUV CCD (the CCD image is rotated by 90°). The left (right) diffraction pattern corresponds to the beam coming on the sample from the top (bottom). The diffraction pattern extends well with a slight overlap at high frequency that can be numerically corrected. This effect could be circumvented by increasing the stereo angle and using an arrangement with two adjacent CCD cameras or a large area PN-CCD detector.*

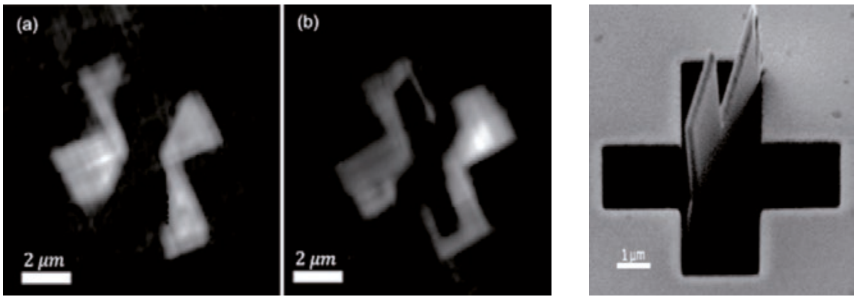


Figure 2: *2D amplitude reconstructions of the sample from the two stereo views. (a) and (b) show the reconstructions corresponding to the top and bottom views of the sample. They are obtained as the coherent averages of, respectively, 45 best reconstructions from independent runs of the CDI algorithm. Each view reaches a spatial resolution of 90 nm which allows to observe details of our nanoscale sample. For comparison, we present In the top-right corner the SEM (scanning electron microscopy) image of the sample observed at a 45° angle.*

Figs. 2(a) and (b) show the amplitude reconstructions of, respectively, the bottom and top diffraction patterns, corresponding to the top and bottom views of the sample, as the average of several independent runs of the phase retrieval algorithm. The spatial resolution of each view is measured to be 130 nm. Differences between the two views are clear: the positions of the opaque cross inside the gap vary. No gap is visible between the lid and the hole at the bottom left and top right parts of Fig. 2(a).

The method allows gaining qualitative 2D structural and spatial information from two observation angles in one acquisition. However, it is possible to go further and gather some quantitative depth information from those images. Indeed, from the pair of reconstructed views of the sample one can compute the disparity map. Disparity refers to the distance between two corresponding points in the two images of a stereo pair. By matching each pixel from one image to the other, one can calculate the distance between them to produce an image. We attribute then the disparity value for that pixel to the corresponding image. The disparity map can, then, be converted into depth information by a simple equation given the geometry of our setup:

$$z(P,\theta) = \frac{d(P)}{tan\theta_1 + tan\theta_2}. \quad (1)$$

In equation (1), z is the relative depth value of the point P of the object, $d(P)$ is P's disparity value and θ_1 , θ_2 are the angles between the plane perpendicular to the CCD and each stereo beam, respectively. From eq. (1) one can notice that the resolution on the depth axis increases with the angle between the two illuminating beams. However, there is an upper limit for this angle which depends on the sample's structure, defined by a minimal presence of identical features in both views, mandatory in order to be able to calculate the disparity values.

Figures 3(a), (d) and (b), (e) show the results of simulations. (a) and (b) present the disparity maps, while (d) and (e) show snapshots of the 3D reconstructions. On the disparity map of Fig. 3(a), which corresponds to a pure amplitude sample, some information is missing due to the lack of common details visible in both views. This brings on evident artefacts in the reconstruction (Fig. 3(d)), where the lid is linked to the membrane.

In Fig. 3(b) and (e), on the other hand, the simulation was realised with a phase sample. Having two stereo views with information on the phase shifts unveils the existence of superimposed planes, which makes possible the retrieval of disparity values on structures which were before hidden behind the membrane. This allows a 3D rendering with fewer artefacts and more details on the structure of the sample.

Figs. 3(c) and (f) show the experimental results from the image reconstructions of Figs. 2(a) and (b). While the cross shape of the hole in the membrane is clearly visible, the reduced signal quality makes the reconstruction of the 3D lid shape more difficult. Note that the cross presents the same non-real connections with the membrane as in the simulation of the pure amplitude sample. Our geometry leads to a voxel size of 96x96x146 nm^3. However, due to the reduced quality of the reconstruction, the actual depth resolution cannot be estimated.

The method described above can be designed for any coherent X-ray beamline and applications are foreseen in single-shot 3D structural imaging of high-impact systems, ranging from biological samples to ultrafast physical processes. A demonstration using data from a soft X-ray synchrotron experiment is also performed and is available in the Nature Photonics paper (see reference below).

We expect that the process will have a major influence on the 3D structure imaging of individual macromolecules and see potential applications in biology, medicine and industry. Other machine learning algorithms are expected to have a huge potential in those fields. For example, the protein structure of a virus, which has a crucial influence on the function and behaviour of a virus and plays a decisive role in medical diagnoses, could be investigated quickly and with little effort in the future by using face recognition type algorithms.

Hamed Merdji (LIDYL)

J. Duarte et al., Nature Photonics 13: 449-453, 2019

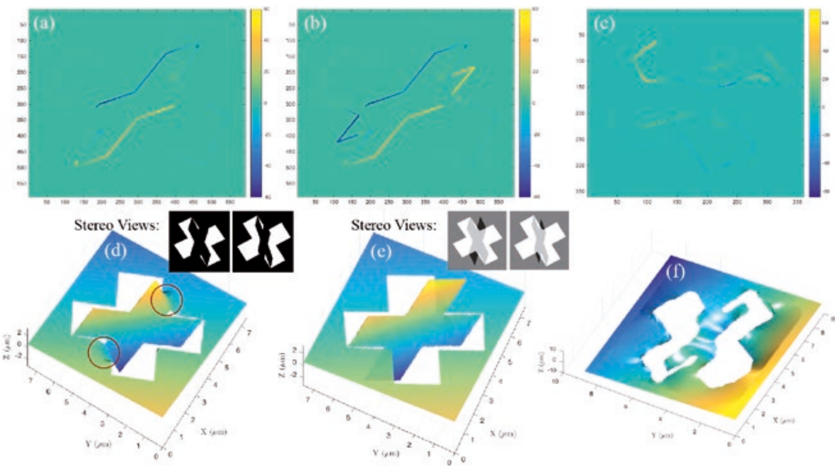


Figure 3: *Disparity maps and 3D reconstructions of the sample. (a), (b), (c): Disparity maps obtained from the correspondence between the right and left views, in this order – bottom and top for the experimental case. The colour scale is defined in pixels. (d), (e), (f): 3D reconstructions of the sample. While (a) and (d) correspond to a numerical simulation performed with an amplitude 3D sample in the experimental geometry, (b) and (e) show the same results assuming a phase sample – different refraction index materials for the cross and the membrane with a cross-shaped cut. (c) and (f) present the experimental disparity map and perspective reconstruction from the images shown in Fig. 3(c) and (d). Note that the colour scale represents the depth value z, for better visualization.*

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2 x 10 PW High Power Laser System installed in the large laser hall at ELI-NP.

Progress at ELI – Nuclear Physics: High Power Laser System passes tests

In September 2019, the High Power Laser System (HPLS), built by Thales, at the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) in Măgurele, Romania, successfully passed all the commissioning tests.

HPLS is a dual front-end chirped pulse amplification system with two optically-synchronised parallel amplification arms, operating at 810 nm central wavelength and pulse duration of about 23 fs at the six outputs. Extensive qualification tests were performed for two outputs with 100 TW peak power at 10 Hz, two outputs with 1 PW at 1 Hz and two outputs with 10 PW at a one shot per minute repetition rate.

The fully amplified pulses were attenuated before compression and measured in full aperture mode, after compression. Strehl ratio of the beam for all the six outputs was 0.9 while the beam pointing stability was in the 2-5 microradian range. When testing the amplifiers, more than 80 consecutive shots were observed at 300 J and one shot per minute, while on the intermediate amplifier more than 36000 consecutive shots at 1 Hz and about 35 J/pulse were registered in 10 hours of operation.

The laser beam transport for the 55 cm aperture, 2 x 10 PW beams to the experimental areas, built by a consortium formed by Thales and Alsyom, will be commissioned at the end of 2019. The commissioning experiments at lower peak power will start at the end of this year, while the commissioning experiments at 10 PW are planned to start at the end of 2020.

Daniel Ursescu and Calin Ur (ELI-NP)

Laserlab-Europe Joint JRA Meeting and Conference

Laserlab-Europe members and external partners gathered on 9-11 October 2019 in Florence, Italy, for a Joint Research Activities (JRA) Meeting and a Laserlab-Europe Conference, hosted by LENS, the European Laboratory for Non-linear Spectroscopy.

The first two days focused on exchange about the progress and achievements within and across the JRA's that have been performed by subgroups of project members collaborating on a set of research projects. Highlights from the research carried out during the past four years were presented, covering a huge variety of subjects from laser 3D printing of biomaterials to hyperspectral SRS for the detection of microplastic particles and methods of controlling the dose of laser-accelerated proton beams.

The JRA meeting was followed by a one-day Laserlab-Europe Conference where, for example, highlights of external users performing research projects at Laserlab facilities were presented to a broad audience. In addition, there was a panel discussion on industrial relations and collaboration options, examples of successful start-up companies related to research in Laserlab-Europe and an introduction to international laser consortia, e.g. LaserNetUS, the Asian Intense Laser Net and the ELI delivery consortium.

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 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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