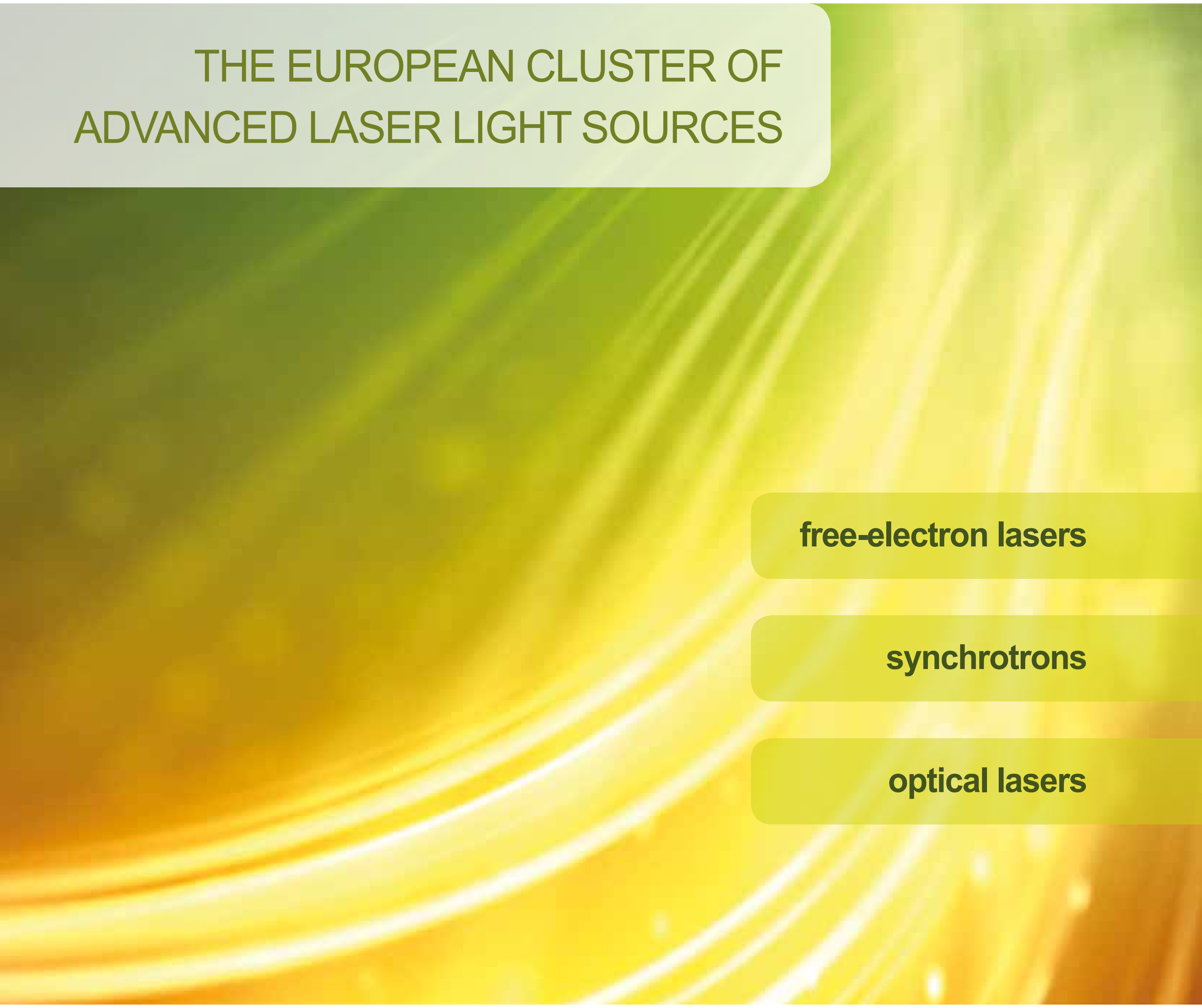
THE EUROPEAN CLUSTER OF ADVANCED LASER LIGHT SOURCES



free-electron lasers

synchrotrons

optical lasers

EUCALL

ACHIEVEMENTS AND OUTCOMES

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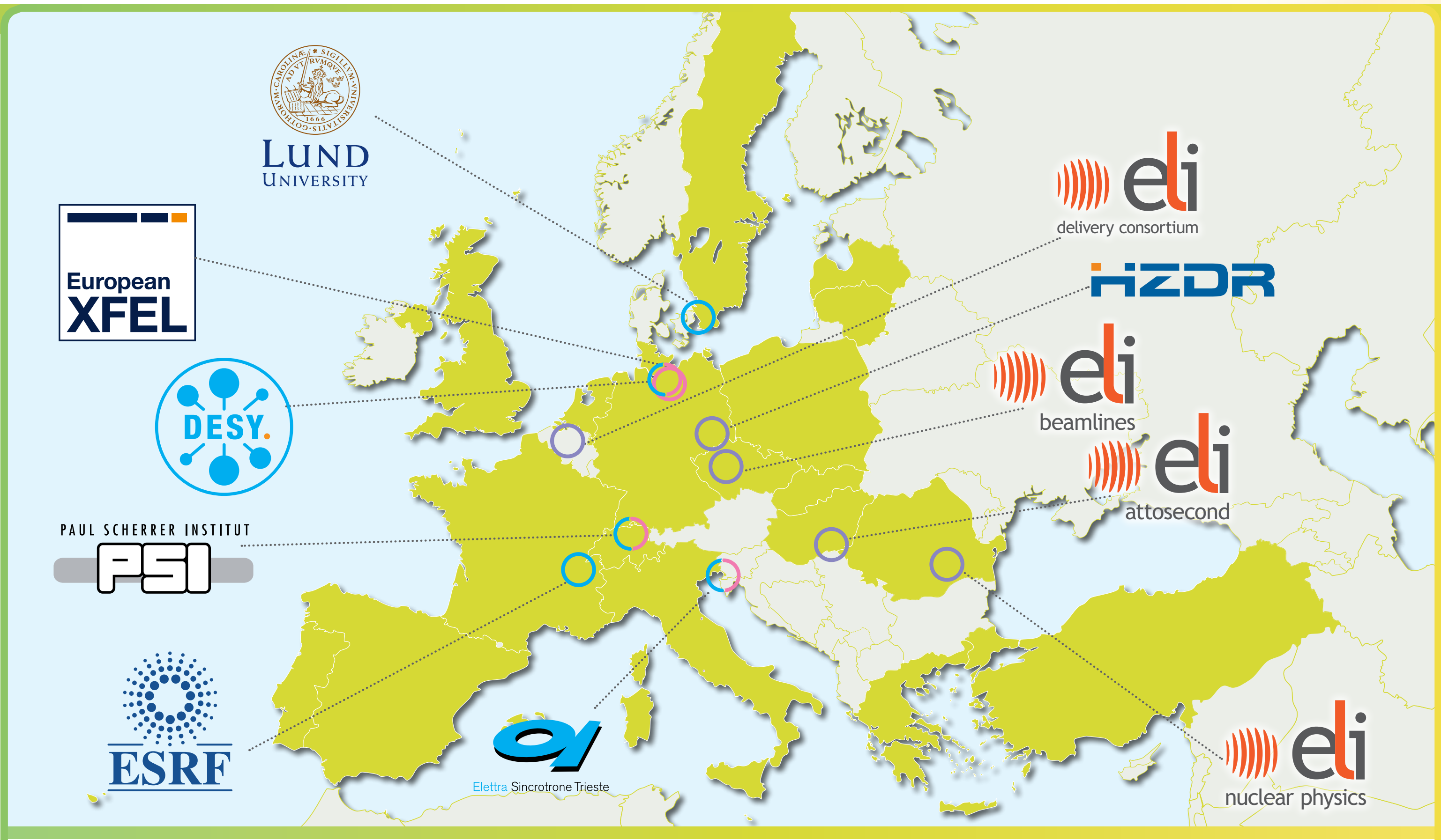
INTRODUCTION

From 2015 to 2018, the European Cluster of Advanced Laser Light Sources (EUCALL) established bridges between some of the world's top photon science facilities that enable scientists to explore the world at the nanoscale. EUCALL focuses on advanced light sources, defined as facilities that provide intense ultraviolet or X-ray light to scientists for the analysis of materials on the nanoscale at ultrafast time scales, enabling direct observation of the fundamentals of chemical processes and behaviour. Advanced light sources have become important locations where the global scientific community can study the basic phenomena of the nanoworld in new ways.

Some of the world's leading advanced light sources are located in Europe. Synchrotrons have well-established user access programmes for advanced photon science experiments. More recently, free-electron lasers (FELs) have brought science using ultraviolet and X-ray light into the laser domain. Both synchrotrons and FELs also use optical lasers on an increasing basis in order to set up special experimental conditions, such as for time-resolved "pump–probe" experiments at the femtosecond time scale. In parallel, optical lasers have become powerful enough to drive secondary ultraviolet and X-ray sources of their own, enabling light source facilities with dedicated user access.

The accelerator-based and laser-based light sources have now begun to overlap significantly. Both have similar technical and organizational challenges, and their research goals and instrumentation are also very alike. Access to the instrumentation at these facilities is in high demand. They are developing state-of-the-art technologies that can be further marketed for other uses.

EUCALL was the first project to analyze and address the overlap between advanced light sources based on accelerators and those based on optical lasers. The project focused on common technical, scientific, and strategic issues, with the goals of optimizing the use of advanced laser light sources in Europe, stimulating and supporting common long-term strategies and research policies, and developing and implementing services that work across the three European Strategy Forum on Research Infrastructures (ESFRI) facilities that EUCALL comprises: the European X-Ray Free-Electron Laser Facility (European XFEL), the European Synchrotron Radiation Facility (ESRF), and the optical laser facilities of the Extreme Light Infrastructure (ELI). This was accomplished in partnership with five national laboratories and universities, along with two networks (see map).



EUCALL comprises three international advanced light sources (the combined three ELI facilities and its delivery consortium, ESRF, and European XFEL) and five national laboratories (Elettra, DESY, HZDR, Lund University/MAX-IV, and PSI), alongside two networks (FELs of Europe and Laserlab-Europe; countries participating in either network are shaded green). The colour of the circles shows the types of advanced light sources founds at each institute: blue for synchrotron, pink for FEL, and purple for optical laser.

This effort has resulted in many new collaborations. Working together, EUCALL scientists of many different backgrounds produced the first start-to-end simulations of light source experiments. They established algorithms and firmware that make data transfer extremely fast—in the tens of gigabytes per second—helping facilities keep up with the enormous data flow their instruments produce. They created prototypes of a flexible, traceable sample delivery system that enables scientists to deal with high repetition rates and that supports the use of different facilities. They created a prototype of monitoring and visualizing light flashes and characterizing their properties, so that scientific users can better interpret their experiment results.

EUCALL also explored the innovation potential and the optimal use of these facilities. Since advanced light sources are wellsprings for new technologies, there is a growing pressure for scientists to help bring these technologies to market for wider society. EUCALL provides recommendations for strengthening technology transfer among European advanced light sources, helping guide scientists and facilities in the commercialization process. In order to ensure that advanced light sources work as efficiently as possible, EUCALL collected input from users on what could help them do their work better, and how these cost-intensive facilities can make the absolute best use of resources towards realizing their research goals.

In this booklet, we present the results and achievements of EUCALL, and you will be able to see how the collaborative framework could break boundaries and make already outstanding, world-leading facilities go beyond to better serve their user communities.

Advanced light sources

Free-electron lasers—facilities such as the European XFEL in Germany are based on a linear electron accelerator and generate ultrashort pulses of intense X-ray laser light. These light sources can determine atomic details of materials using pulses that can resolve changes in timeframes approaching a millionth of a billionth of a second. These time-resolved studies of atomic and molecular structures are used to benefit research in materials science, biochemistry, geo- and planetary science, and more.

Optical lasers—higher-power optical laser technologies have driven the construction of new user facilities with techniques that enable shorter wavelength experiments that can probe shorter timescales. For example, the Extreme Light Infrastructure (ELI), based in Czechia, Hungary, and Romania, enables new investigations into novel methods of particle acceleration, research into extreme states of matter, and time-resolved structural biology.

Synchrotrons—these facilities have a storied history. In the past three decades, synchrotrons have performed Nobel-Prize–winning work in biochemistry and become tools in the development of new materials for sustainable energy like solar panels and batteries. They can enable a broad array of advanced experiment techniques, from classical crystallography to some of the latest time-resolved methods.

SYNERGY

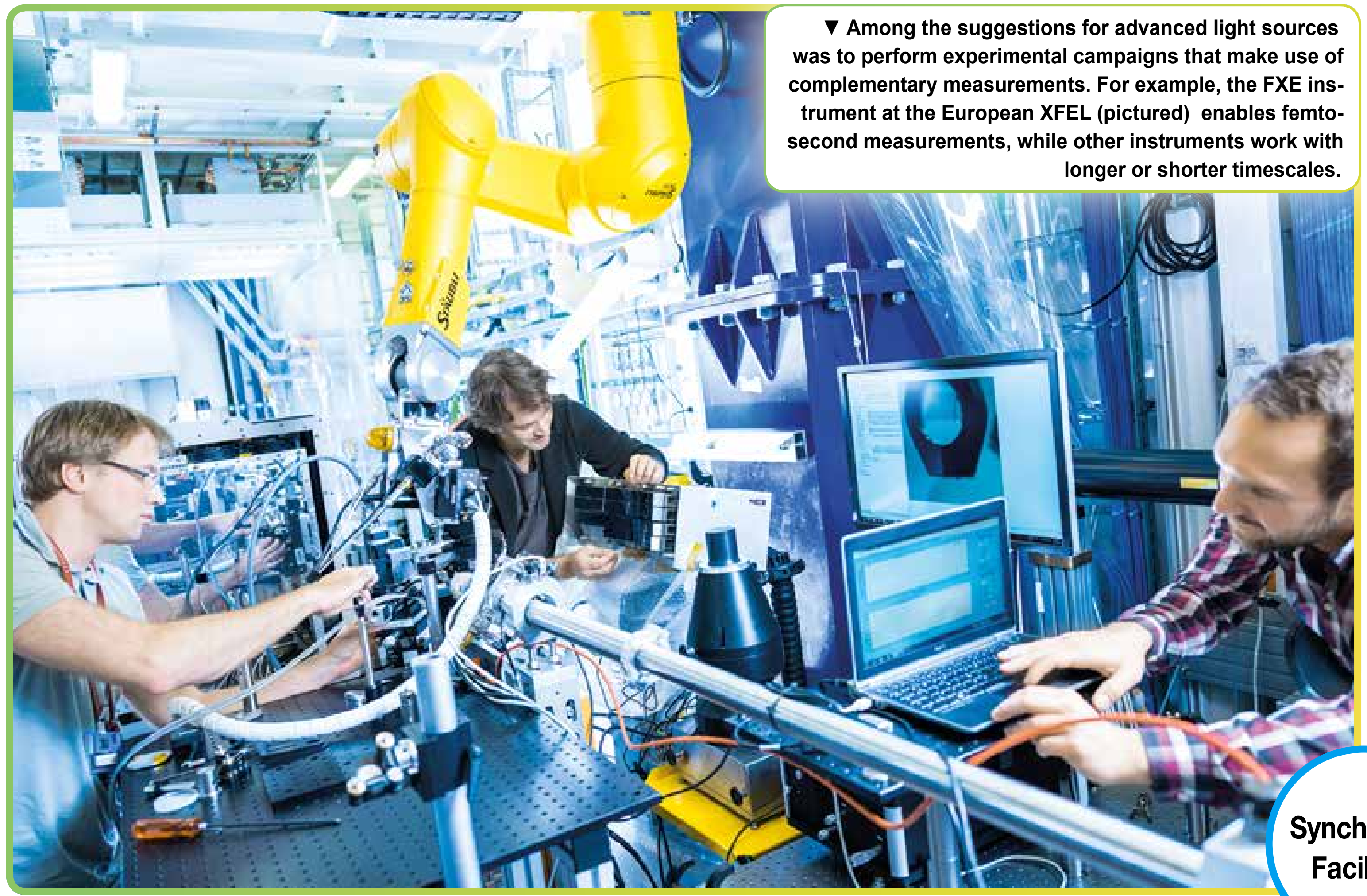
Commonalities between accelerator-based
and laser-based light source facilities

EUCALL focuses on the overlap between accelerator-based and laser-based light sources. It established a sustained collaboration with the aim of harmonizing and optimizing the landscape of advanced light sources. The development of such connections will benefit the scientific users of these facilities through better and more efficient services.

Building on input from users, EUCALL advised how advanced light sources could better suit the needs of the user community at large. EUCALL analyzed the suite of instrumentation at the European advanced light source facilities and provides recommendations for their individual and joint development.

Analyzing the advanced light source landscape

EUCALL compiled detailed information about 22 characteristics at 121 different experiment setups at 17 advanced light sources across Europe. This data collection includes information regarding the properties of the light generated, the types of experimental techniques employed, and the properties of associated technical infrastructure such as optical lasers and sample delivery systems.



▼ **Among the suggestions for advanced light sources was to perform experimental campaigns that make use of complementary measurements. For example, the FXE instrument at the European XFEL (pictured) enables femtosecond measurements, while other instruments work with longer or shorter timescales.**

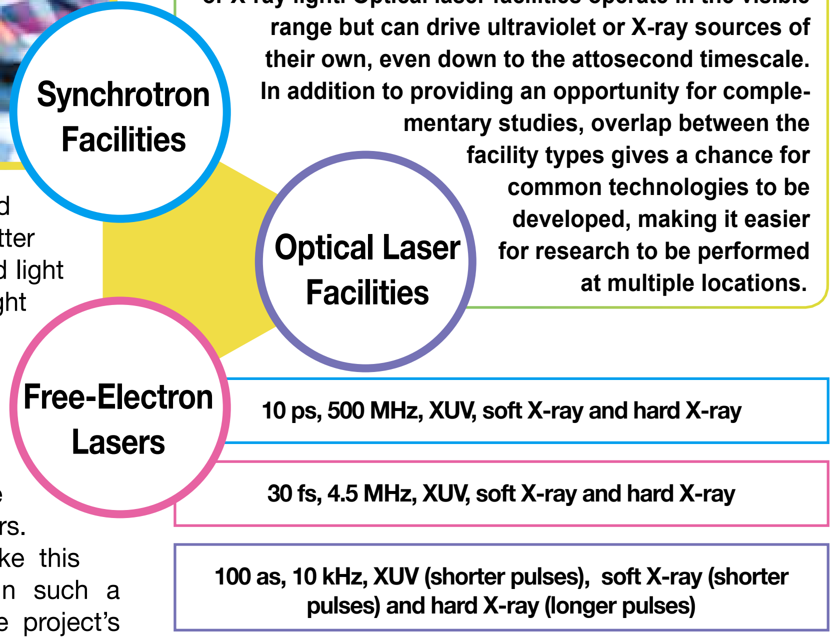
The advanced light source experts involved in EUCALL performed a comprehensive analysis of these data and developed recommendations for optimal use of these facilities, with regard to scientific and user needs. These recommendations include maintaining a varied range of instruments in order to support a broad scope of scientific applications, even providing a certain level of overlapping technologies at the various advanced light sources to increase their availability; encouraging experimental campaigns that make use of complementary measurements at neighbouring advanced light source facilities; or developing FEL and optical laser instrumentation such as to reach the stability, operational performance, and versatility of synchrotron instruments. Additionally, it is recommended that, as technologies for miniaturizing advanced light sources develop, table-top or local laboratory X-ray setups be built and used for preparatory investigations, thereby better preparing experiments at large-scale advanced light sources and more efficiently using these light sources.

Enhanced availability of information via Wayforlight

The collected landscape data were considered to be very useful for users. EUCALL therefore investigated ways to make this catalogue of properties publicly available in such a way that it could be accessible beyond the project's timespan. The information was incorporated into the Wayforlight portal (www.wayforlight.eu), a platform for European accelerator-based light sources.

Wayforlight was created under the EU project CALIPSO, and it is further developed under the Horizon 2020 project CALIPSOplus. The portal maintains a searchable public database of instrumentation at synchrotron and FEL facilities. Using Wayforlight, scientists can find out which facilities might be most suitable for their measurements by comparing the instrumentation available at each. The EUCALL landscape dataset integrated the laser-driven advanced light sources into Wayforlight for the first time. The newly augmented Wayforlight database becomes publicly available in September 2018. Users will now be able to explore the database and directly compare instrumentation at a much larger number of facilities at a greater depth, allowing them to develop more elaborate comparative and repeat experiments at various facilities.

▼ **Characteristics of advanced light sources in terms of their complementary use. Synchrotrons are capable of generating longer pulses of a large range of X-ray light. FELs generate laser-like ultrashort pulses of ultraviolet or X-ray light. Optical laser facilities operate in the visible range but can drive ultraviolet or X-ray sources of their own, even down to the attosecond timescale. In addition to providing an opportunity for complementary studies, overlap between the facility types gives a chance for common technologies to be developed, making it easier for research to be performed at multiple locations.**



Synchrotron Facilities

Optical Laser Facilities

Free-Electron Lasers

10 ps, 500 MHz, XUV, soft X-ray and hard X-ray

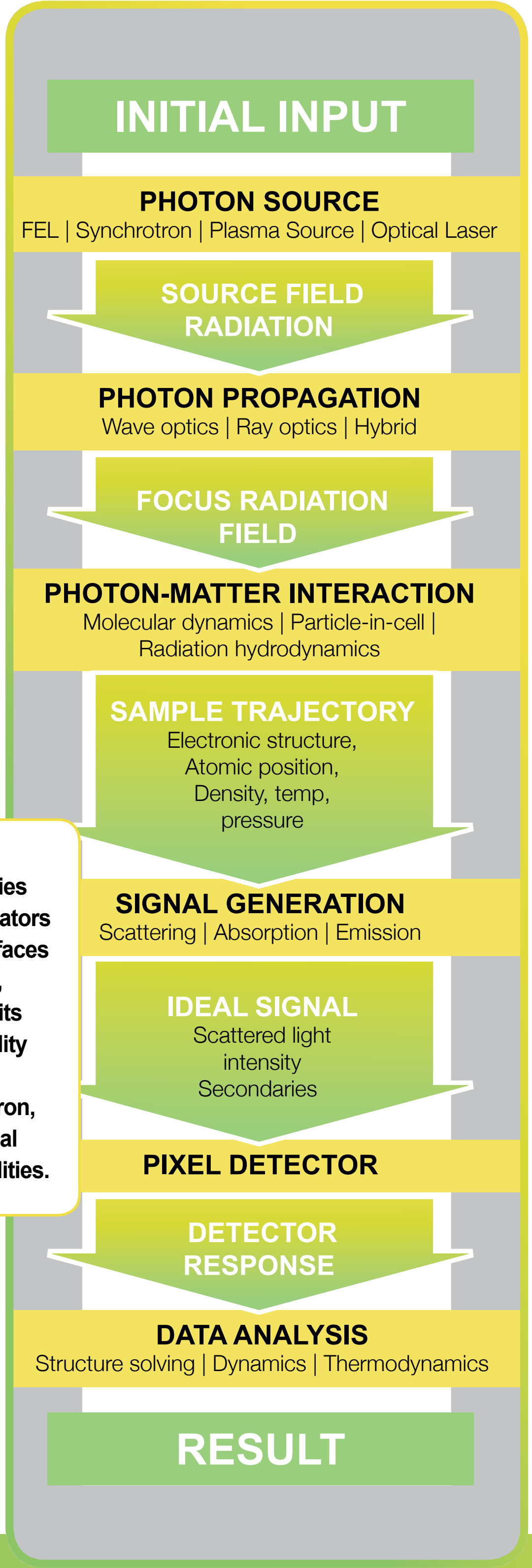
30 fs, 4.5 MHz, XUV, soft X-ray and hard X-ray

100 as, 10 kHz, XUV (shorter pulses), soft X-ray (shorter pulses) and hard X-ray (longer pulses)

> *EUCALL gave a boost to Wayforlight to reach a full spectrum of standardization, now including not only synchrotrons and FELs, but also laser sources. Moreover, it provided the chance to build a sustainable system since data will be more easily transferrable to other websites, to ensure future interoperability.* – *Cecilia Blasetti, international project officer at Elettra Sincrotrone Trieste*

SIMEX

Simulations of Photon Experiments



INITIAL INPUT

PHOTON SOURCE
FEL | Synchrotron | Plasma Source | Optical Laser

SOURCE FIELD RADIATION

PHOTON PROPAGATION
Wave optics | Ray optics | Hybrid

FOCUS RADIATION FIELD

PHOTON-MATTER INTERACTION
Molecular dynamics | Particle-in-cell | Radiation hydrodynamics

SAMPLE TRAJECTORY
Electronic structure, Atomic position, Density, temp, pressure

SIGNAL GENERATION
Scattering | Absorption | Emission

IDEAL SIGNAL
Scattered light intensity
Secondaries

PIXEL DETECTOR

DETECTOR RESPONSE

DATA ANALYSIS
Structure solving | Dynamics | Thermodynamics

RESULT

► The possibilities for calculators and interfaces in SIMEX, showing its applicability for FEL, synchrotron, and optical laser facilities.

As advanced light source technologies have developed, scientists have written software to simulate different components of these facilities. However, none had tackled the entirety of a complete experiment, from the generation of light to the results—at least until EUCALL scientists developed SIMEX. SIMEX is a unique simulation framework that uses some of most advanced simulation tools and integrates them to mimic an entire light source beamline. It is a flexible, modular system that can be tailored for use at potentially any advanced light source.

Chains of calculators and interfaces

SIMEX is akin to a train: each car has to fit into the next just right, and what happens with the first cars affects the ones that come thereafter. The framework's developers worked from a prototype developed between several institutes under the leadership of European XFEL[1]. In the early version of the software, scientists could input the different features of their X-ray FEL experiment and get a model diffraction pattern. SIMEX expanded upon this framework by integrating simulations of different constituent parts of advanced light source facilities. This means SIMEX could now potentially model an experiment at any advanced light source.

SIMEX works by placing different constituent simulations, or "calculators", in a chronological order. The simulation for the focusing of the light onto the sample is followed by the simulation for interaction of the light with the sample, and so on. At the end, the simulation acts as a virtual version of the desired facility beamline.

In between the calculators are interfaces, which take the output of one calculator and make it standardized so as to turn it into the input of the next. At benchmarking tests at the LCLS X-ray FEL in California—which hosts some of the beamlines first modeled in SIMEX—scientists found that SIMEX data outputs match well with actual experimental data on biological imaging experiments.

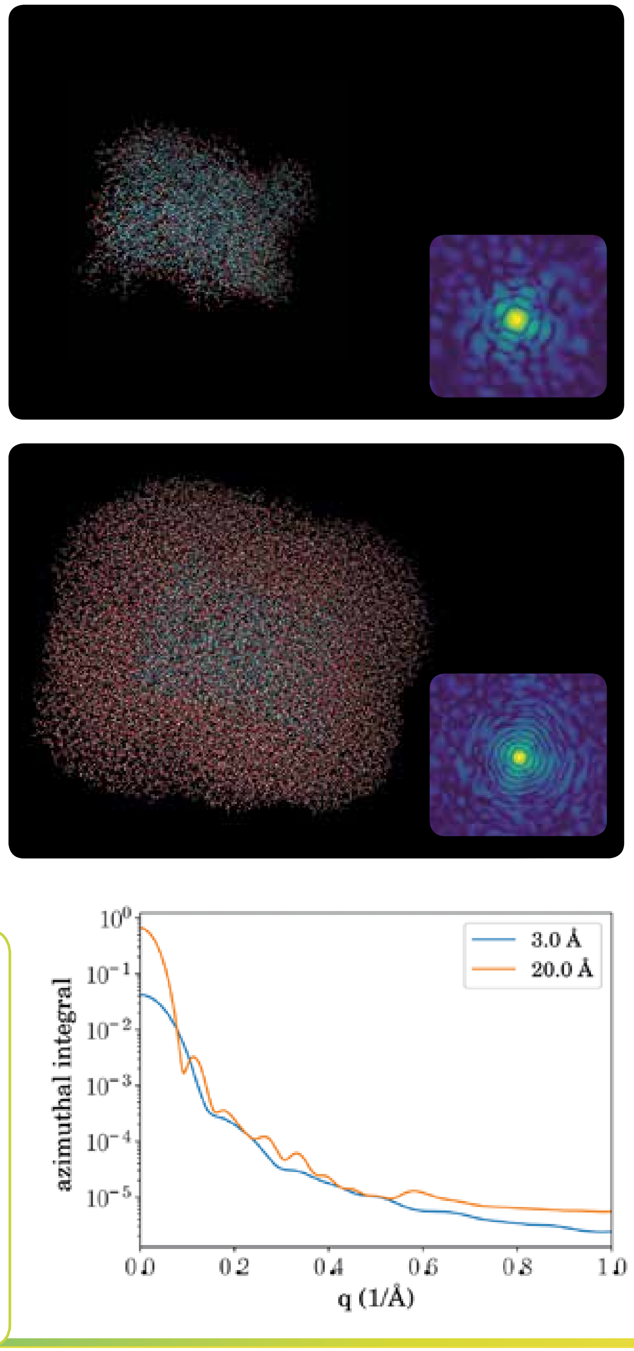
> ***SIMEX to me not only provided a vision of the future of start-to-end simulations, but also a first implementation of a real-world solution that I have high hopes to be the future standard in the field.*** *– Michael Bussmann, scientist at HZDR*

An essential tool

One promising use of SIMEX is the ability to test the feasibility of experiments before they are performed. This feature will allow scientists to demonstrate that an experiment can be carried out with reasonable results ahead of the experiment allocation. Also, scientists can ahead of time determine the best conditions to optimize data collection, saving experiment teams precious time at the facility that would otherwise be used for tinkering with settings. As SIMEX grows in its flexibility, it will be able to simulate more instruments at more facilities.

Tools such as SIMEX allow scientists to use advanced light sources more efficiently. They also support a widening of scientific applications through the ability to test the feasibility and to optimize the control of experiments at the facilities.

A further use of SIMEX is that it can be employed by new users of advanced light sources to learn about how to design and run a photon science experiment. SIMEX is foreseen to be integrated into an e-learning platform to train the next generation of users about how to plan and perform experiments at advanced light sources.



► An example SIMEX simulation of a structural biology experiment on proteins surrounded by layers of water of varying thicknesses. The goal of this simulation was to mimic how the water could affect the results of the experiment. TOP AND CENTRE: 3D visualizations of the protein and the surrounding water layer of thickness (top image) 3 Å and (centre image) 20 Å. The results from SIMEX, showing variations in the diffraction patterns, are insets in the molecular model. The patterns show that the sample particle has gotten larger with the additional water. BOTTOM: The simulated data, when translated to a line graph projection, reveals that the water obscures the physical details of the protein by making the sample appear smoother than it really is.

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[1] [Yoon et al., Scientific Reports (2016)]

UFDAC

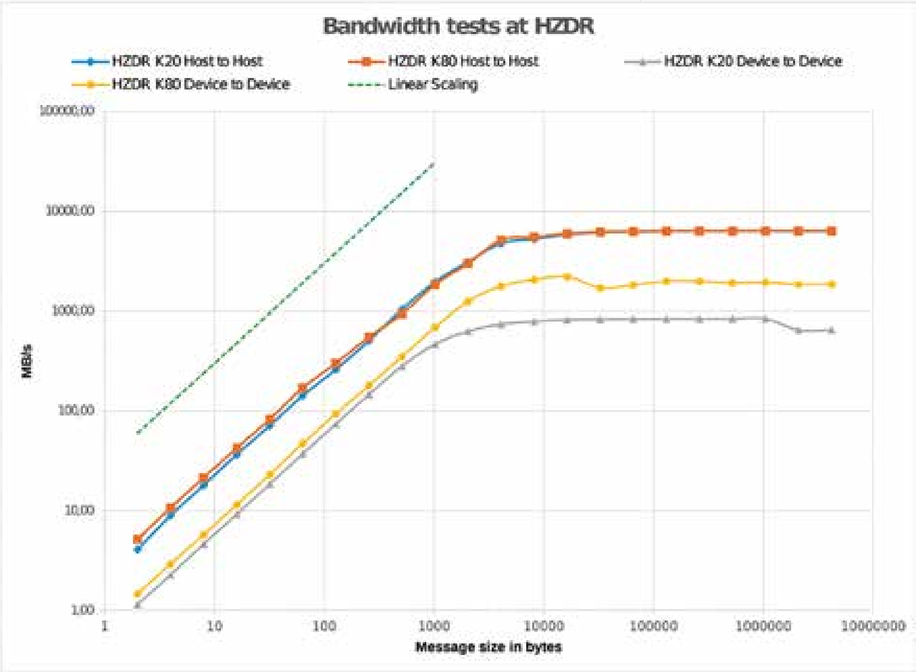
Ultrafast Data Acquisition

Science experiments in the past decade have seen an enormous growth in the amount of data generated. As the repetition rates of advanced light sources increase and their detectors become faster with higher dynamic ranges and frame rates, advanced light sources need to increase the rate of data acquisition to be able to cope with unprecedented amounts of incoming information. Also, the ability to visualize experimental data and to extract preliminary results is of highest importance to the scientists using these facilities, as both capabilities enable them to perform more successful, efficient experiments.

Meeting the challenge of ultrafast processing of big data

Processing, storing, and analyzing data is no trivial matter in any case, let alone at advanced light sources. Individual instruments at advanced light sources can produce data at the level of hundreds of gigabytes per second, meaning even terabyte storage systems would fill up in minutes. This data amount is mostly generated by complex detectors or diagnostic systems needed for carrying out experiments, and each provides data rates on the order of gigabytes per second. Latency, or the time it takes to process and record the data, is also an issue, as it can cause a traffic jam of sorts on data servers, potentially risking the loss of data and affecting results. Scientists need their data to move from detector to storage fast enough to clear the way for the next data set—operations requiring the transfer of massive amounts of information in a fraction of a second. The data need to be recorded in a standardized format that can be read later.

To help ameliorate this issue, UFDAC scientists worked on a suite of algorithm libraries that deliver scientists their data in a highly reliable way at the highest data flow. By coordinating the efforts of data transfer experts and programmers, UFDAC was able to push the boundaries of transfer speeds and online processing.



◄ **UFDAC algorithms are pushing data transfer to its limits. UFDAC worked on pushing transfer rates to their theoretical maximums, avoiding unnecessary involvement of computing resources and intermediate copies of data into the host memory as the data moves from detector to processing unit. UFDAC algorithms are able to reach the current physical limits between host memory and processing unit (host to host, shown in blue and orange), no matter which hardware platform is used. The transfer rate between processing units (or detector interface and processing unit—device to device, shown in gold and grey) is still under development. "K20" and "K80" refer to the type of processor card used in this study.**

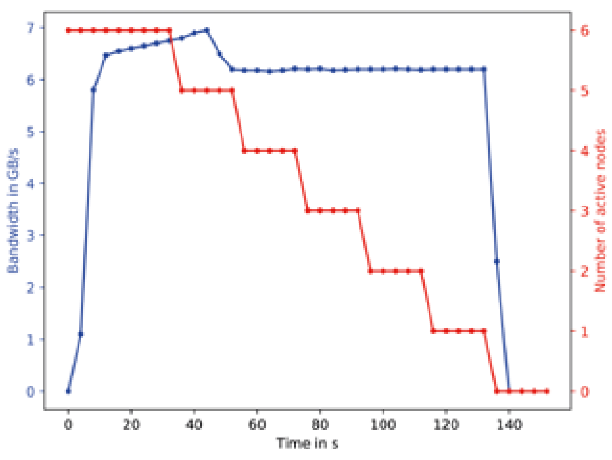
UFDAC firmware is a general solution to the data transfer problem that works at as many facilities as possible. UFDAC used a framework called RASHPA, developed at ESRF through the earlier EU-funded project CRISP, as a basis for new data pipelines that decrease processing time. RASHPA employs high-speed data connections inside computers, and UFDAC scientists experimented with longer physical connections extending these high-speed links between the detector and the processing unit.

With the improved data pipelines, transfer using UFDAC algorithms can reach as much as 10 or 20 GB per second per individual data source, in a highly generic and easy-to-use way as compared to commonly available solutions. This helps with online processing and keeps data moving from detector to data server at a more continuous rate—something critical as detectors continue to record more complex data more quickly.

Online processing solutions

Data needs to be manipulated as soon as it is acquired by a detector, which is known as online processing. To help online processing become more efficient, scientists had to learn how to deal with different processors using FPGAs and GPUs. UFDAC algorithms can adapt to environments regardless of the processor type, in part through a program called Alpaka, which automatically fits a data acquisition setup to a standardized software solution. The algorithms temporarily reorganize the data so calculations can be performed in an efficient parallel manner, and a later algorithm returns the data to its original structure for recording.

Online processing also increases the efficiency of advanced light sources. Since information is processed immediately, scientists can get real-time pictures of what incoming X-rays look like or how their samples are interacting with the light. For example, EUCALL's PUCCA group developed a timing tool that allows scientists to monitor the difference in time between two incoming pulses of light down to a millionth of a billionth of a second. Instead of learning only after the experiment that settings needed adjustment, they can now adjust the timing on the fly, thanks to UFDAC algorithms—giving them the chance to get better data during one allocated experiment time, instead of needing to come back to an advanced light source numerous times to perform a similar experiment to acquire better data.



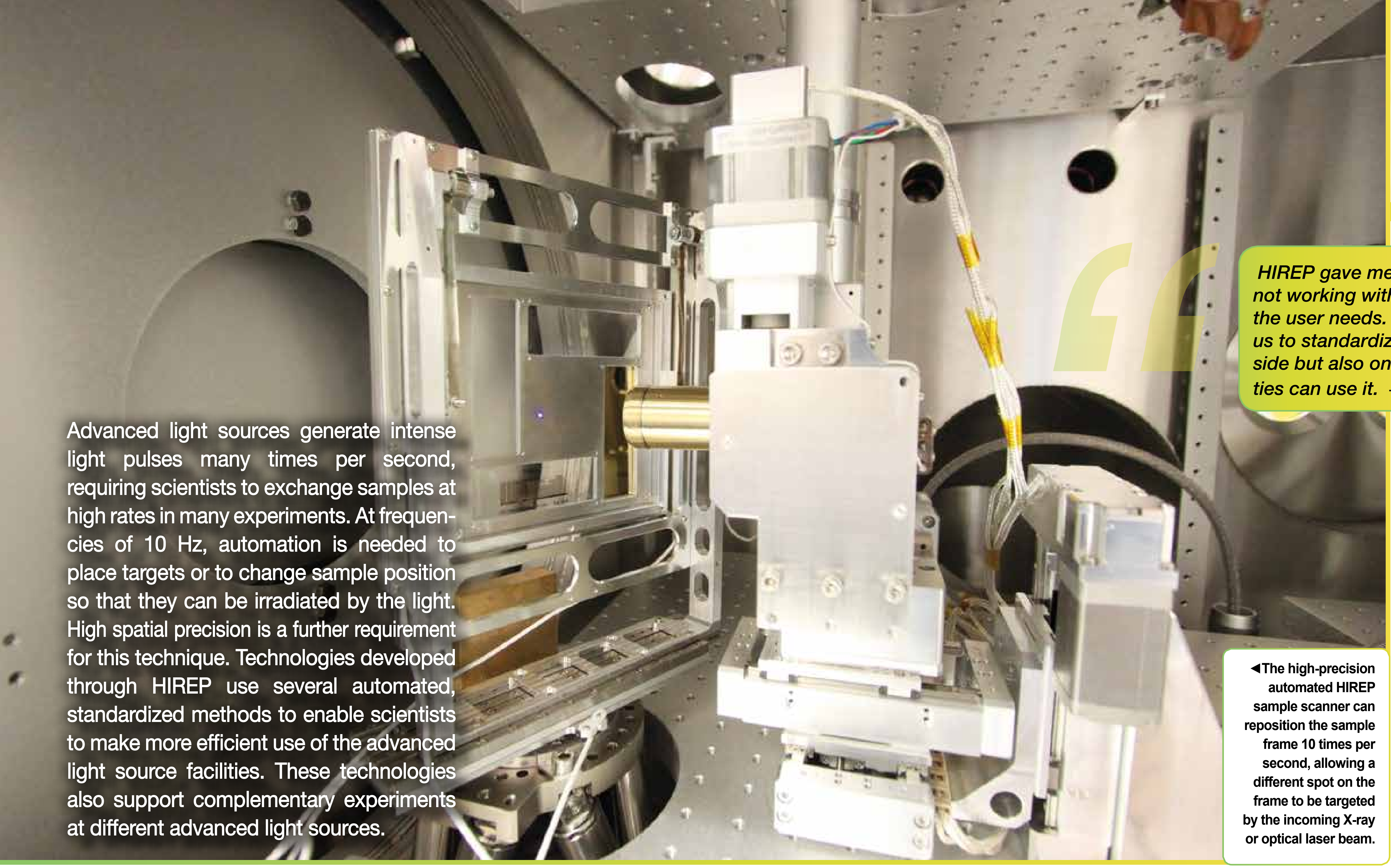
▲ **UFDAC's algorithms are resilient, allowing data transfer to occur without interruption even as the number of channels, or nodes, through which information can flow become unavailable. This test allowed data to be transferred at a rate between 6 and 7 GB per second, even as the number of nodes dropped to just one. The transfer rate did not drop off until the last node shut down.**

Resilient methods

UFDAC's solutions for the data flood also help deal with the unexpected. If an outage caused by technical problems or overload on certain pipelines occurs, then the frameworks developed for UFDAC can respond by making the data flow a bit like water—taking a path of least resistance. By using different, much less occupied pipelines in the system, the data flow can continue allowing the system to function at a similar speed without risking losing valuable information. This resiliency is meant to boost performance for high-quantity data acquisition.

HIREP

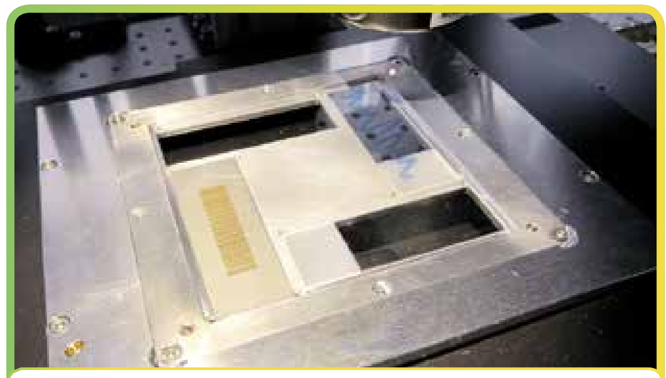
High Repetition Rate Sample Delivery



Advanced light sources generate intense light pulses many times per second, requiring scientists to exchange samples at high rates in many experiments. At frequencies of 10 Hz, automation is needed to place targets or to change sample position so that they can be irradiated by the light. High spatial precision is a further requirement for this technique. Technologies developed through HIREP use several automated, standardized methods to enable scientists to make more efficient use of the advanced light source facilities. These technologies also support complementary experiments at different advanced light sources.

◄The high-precision automated HIREP sample scanner can reposition the sample frame 10 times per second, allowing a different spot on the frame to be targeted by the incoming X-ray or optical laser beam.

> *HIREP gave me the opportunity to learn from other groups not working with high-power lasers to better understand what the user needs. The design of the target system has relied on us to standardizing our technical solution—on the mechanical side but also on the side of the software—so that many facilities can use it.* – *Daniele Margarone, leading scientist at ELI-Beamlines*



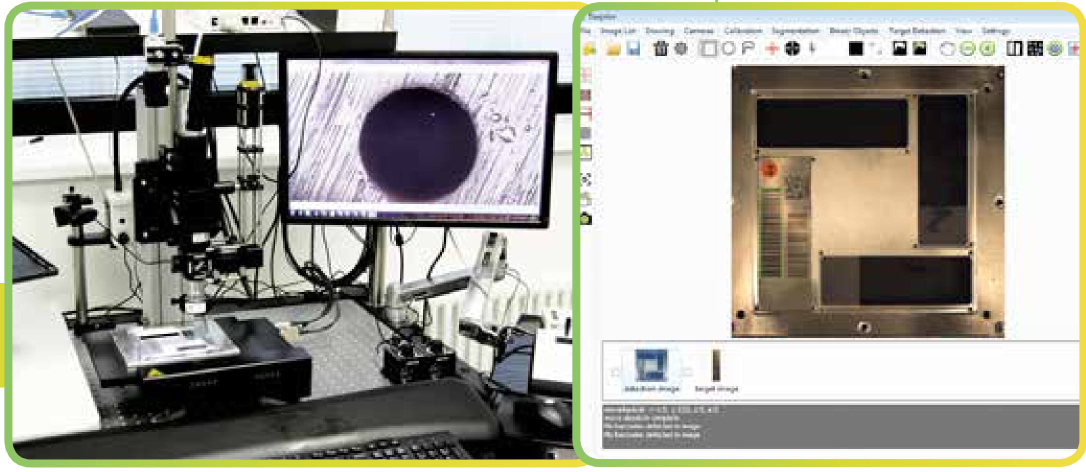
▲ The HIREP standardised sample frame holds solid sample foils for experiments performed at advanced light sources. The frame is sturdy enough to be reused multiple times. The foils are attached to the frame where the three rectangular holes can be seen. A barcode on the frame (seen to the bottom left of where the foils are attached) links the information about sample targeting to the automated alignment system, helping scientists do research at a high repetition rate and handle potentially thousands of samples in one experiment.

Standard sample infrastructure

HIREP scientists developed two sets of standard sample frames for use at various advanced light source instruments. One is a frame for biological samples, with evenly spaced conical grooves that act like wells into which cryogenically frozen biological samples are delivered. The second frame holds solid samples such as foils, possibly carrying deposited thin films for investigation. HIREP's special software uses a form of artificial intelligence to identify areas of interest on these foils for the experiment. A sample scanner and a rotating stand automatically and precisely align the foils in the frame relative to the pump or probe beams and move the samples to match a 10 Hz repetition rate.

Support for complementary experiments

The sample technologies developed by HIREP enable complementary experiments at different advanced light sources. The setup can be adapted to any advanced light source instrument. Every frame has a specific barcode attached to it that is used for associating the frame with a specific sample and allows for linking the information about that specific frame, stored in the software, with the actual measurement. A central database acts as a repository for data collected using the HIREP setup, allowing data to be called up by users regardless of what institute they are currently doing work at. Comparisons of results at different instruments are then easier to perform, enabling complementary experiments and allowing users to learn more from experiments at several facilities.



▼ Target identification hardware and software helps scientists find potential areas of interest on the sample. A microscope (left) scans the sample frame and uses artificial intelligence to identify regions of interest to be targeted. The location of these spots is aligned with the frame (right) and this information is communicated to the sample scanner via the barcode on the frame. The scanner then automatically aligns the spots of interest with the X-ray or laser beam.

PUCCA

Pulse Characterization and Control

> *They are all X-rays, but the challenge in producing and characterizing them is different for each kind of light source. PUCCA benefits from the exchange of the different approaches and the experience gained between the different facilities.* *– Stephan Klumpp, scientist at DESY*

As advanced light sources generate ever shorter and more intense flashes, it becomes more of a challenge to monitor the properties of those flashes. For FELs and optical lasers, this is particularly important, as their light generation methods are not as stable as those of synchrotrons, necessitating the ability to characterize and control the properties of every flash of light. EUCALL developed a suite of tools that deal with these ultrashort, intense pulses.

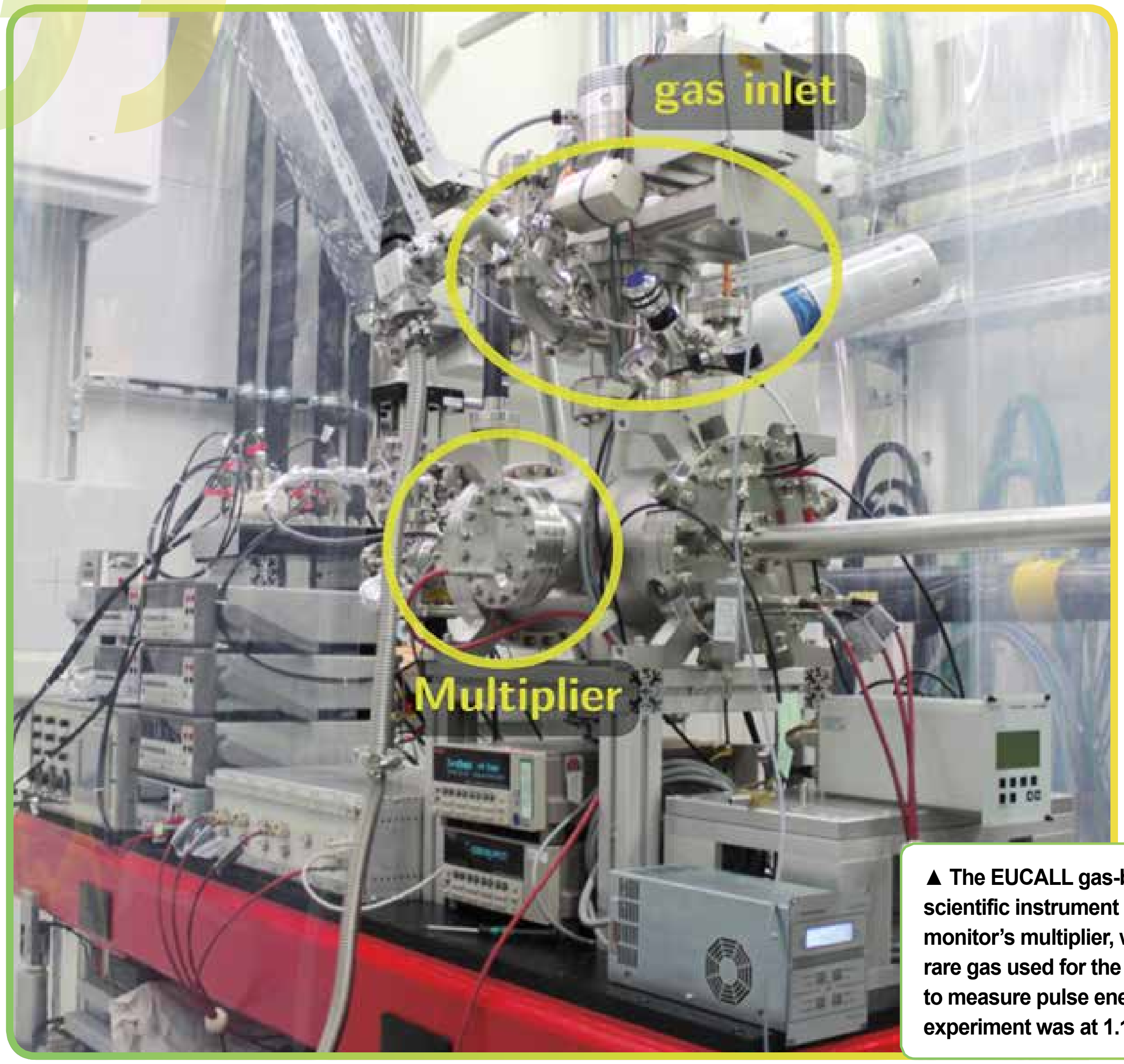
Monitoring intensity and shape

In PUCCA, EUCALL scientists developed new methods of monitoring hard X-rays. DESY developed a gas-based monitor that characterizes both high and low intensity pulses at repetition rates keeping up with the megahertz repetition rates of accelerator-based facilities. Scientists learn about the shape of the beam and its propagation along the experiment station using devices called wavefront monitors. A method developed by EUCALL scientists at ESRF uses a simple soft membrane to produce a scattering pattern from a partially coherent hard X-ray beam at two different detectors simultaneously. From a comparison of the two patterns, the wavefront is calculated. In combination with algorithms developed through UFDAC, online wavefront measurements can be performed, allowing users to change their settings on the fly and know about the light that is incoming towards their sample.

Timing tools

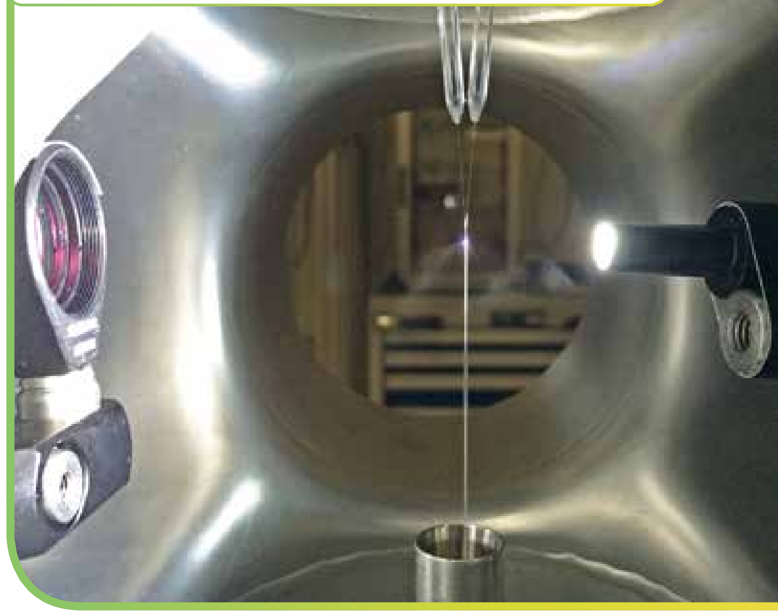
Using what is known as a pump–probe experiment, scientists observe time-resolved chemical and physical processes. At FELs and optical laser facilities, these time scales get down to a millionth of a billionth of a second or lower, making atomic vibrations and other movements visible. Performing these experiments using two different sources of light requires what scientists call a “timing tool”: an apparatus measuring when a reaction is set off by a pulse from an optical laser, as well as at what point in its progression a subsequent X-ray pulse images it. One of the timing tools developed by PUCCA measures the delay between “pump” optical lasers and “probe” X-ray pulses by measuring the changes, which are induced by the laser and observed using the X-ray pulses or vice versa, in the reflectivity of flat sheets of a stream of liquid.

The result is a time readout that is precise to the needed experimental timescale. A different, accelerator-based approach has been pursued using a technique called terahertz-streaking, which maps the time between pulses as well as the pulse shape and records the data using a fast camera.



▲ The EUCALL gas-based X-ray monitor was set up at the European XFEL’s FXE scientific instrument and tested during the instrument’s commissioning in 2017. The monitor’s multiplier, which boosts the X-ray signal, and the gas inlet, which delivers the rare gas used for the monitoring, are marked. Using this setup, the scientists were able to measure pulse energies at the rate at which the X-ray pulses arrived, which for that experiment was at 1.1 MHz.

▼ The liquid flat sheet that is used for the timing tool, which enables scientists to determine the delay between two laser pulses arriving at the sample region for the experiment. The liquid sheet is made by merging two smaller liquid jets, and the combined jet is thinner than a human hair. The laser pulse and the X-ray pulse distorts the point where the two jets merge, changing the jet’s reflectivity.



> *The instrumentation developed by PUCCA allows us to fully exploit the new X-ray sources, for example with the wavefront sensor for accessing the optical properties of the X-ray beam. The specificities of the pulsed light delivered by these sources made us deal with approaches very far from traditional ones and design really innovative solutions.*
> *– Ruxandra Cojocaru, postdoctoral fellow at ESRF*

INNOVATION

Enhancing the innovation potential of advanced light sources

In order to better understand how the innovation potential of advanced light sources in Europe could be developed, EUCALL studied and analyzed the technology transfer policies of 14 different light sources in Europe, as well as in the USA and Japan. From this, EUCALL has developed a set of best practices especially useful for new and recently commissioned advanced light sources in defining their technology transfer policies.

It is recommended that advanced light sources carefully evaluate technological and scientific developments with respect to their possible marketability, and that they also train researchers from an early stage to recognize which inventions can or should be protected and which can be directly published. It is also suggested to avoid establishing too many expensive patents, especially if these are to be later abandoned. Advanced light sources are recommended to dedicate staff to perform proprietary research projects for commercial users, while also engaging with external mediator companies to reduce the requirements on facility scientists performing, analyzing, and reporting commercial measurements.

Innovation networks

EUCALL proposes a platform for networking and co-operation between the light source facilities' innovation offices. Such a network would be used to initiate new collaborations, support the introduction of a new series of common key performance indicators for measuring the economic impact of light sources, help develop common technology transfer policies for multiple light sources, establish an EU-wide platform for disseminating patents and spinoffs, and establish links to former light source scientists who now work in industry as ambassadors for technology transfer at light source facilities.

Training programmes

Generally, researchers work by developing technologies to further their studies and publishing the results. However, having at least a basic understanding of innovation and marketing practices is becoming a part of the scientific process as well. EUCALL recommends that research infrastructures train young scientists in innovation processes. Researchers receiving such training can identify intellectual property that is appropriate for protection, take steps in protecting it, and make moves to commercialization. This training involves getting the scientists acquainted with how and when to engage their technology transfer offices while performing research.

How advanced light sources work with industry

Joint development of technology: Advanced light sources may directly collaborate with industrial partners to help develop their technologies. The facility provides the requirements, the partner develops the technology, the facility provides support, and the partner may then sell the new technology.

Protection and commercialization of intellectual property: New technologies can be protected with a patent. A technology transfer office assists scientists with navigating this process and determining when patents should be pursued or abandoned. Patented technologies can be licenced, or spin-off companies can be built around a specific patent or set of patents—direct measurements of a research infrastructure's economic impact.

Commercial access to advanced light sources: most advanced light sources make a small percentage of their beamtime available only for proprietary research for some specified fee. Advanced light sources can become unique resources for commercial firms to advance their own R&D and potentially gain an advantage over their competitors.

> *EUCALL gave me the opportunity to share best practices, experience, and specific visions with the other technology transfer offices across Europe. This background was very useful for defining the approach at our new industrial liaison office for successful exploitation of our knowledge and technology.*
>
> *– Antonio Bonucci, leader of Industrial Liaison Office at European XFEL*

IMPACT

EUCALL's effect on the landscape of light source facilities

> *EUCALL confirmed that there are a number of scientific and technical challenges that are indeed best addressed through the joint collaboration of these world-class facilities. We've shown that accelerator-based and laser-based light sources are complementary on a number of measures, and have identified many research synergies and potential future capabilities that should be further explored—they can only strengthen Europe's position as a leader in science research, while also contributing to Europe's economic future through the fostering of innovation.*
>
> *– Florian Gliksohn, Associate Director of ELI Delivery Consortium*

EUCALL set out to support the optimized use of advanced light sources in Europe, develop and implement services that work across the three ESFRI partners in EUCALL, and stimulate and support common long-term strategies and research policies. Each of these goals was addressed through a variety of collaborative efforts from the partner institutes.

In order to push for the optimization of use of advanced these facilities in Europe, EUCALL developed tools that make light sources more efficient for scientific users and enable better usage and results.

SIMEX helps scientists better prepare for experiments and understand their possible outcomes ahead of time. UFDAC algorithms and a flexible software framework help scientists benefit from high-repetition rate experiments better by expediting the data flow from detector to storage and allowing scientists to see immediate online results. Automated, standardized equipment developed through HIREP gives scientists the ability to refresh samples at a 10 Hz rate and enables reliable and precise alignment of those samples with the beam. PUCCA diagnostic devices help users characterize their beams, enabling measurements at higher time resolutions and with improved understanding of how they come to their results. EUCALL supported the collection of a homogenized set of light source instrumentation data as well as the clear and sustainable presentation of that data so that scientists can more easily find out what facilities and instruments suit their experiments best.

EUCALL funded experience exchange programmes between synchrotrons, FELs, and optical laser facilities and gave bursaries for students to attend workshops, conferences, and summer schools in order to train the next generation to use the broad landscape of advanced light sources to explore scientific and societal challenges.

These results also lead into services available at all of the three ESFRI light sources (ELI, ESRF, and European XFEL), as well as at the national facilities. To provide a few examples: The HIREP sample delivery system is being implemented at selected ESRF and European XFEL instruments, and ELI plans to integrate the hardware into its experiment stations. PUCCA's wavefront sensor was developed at ESRF and optimized for use at European XFEL and ELI-Beamlines. SIMEX and UFDAC's technologies will be usable at any advanced light source. The improved Wayforlight database helps scientists search for and match up instrumentation to their experiment goals. Innovation activities between the ESFRI and national facilities will support improved and more efficient exploitation of the commercial potential of all research infrastructures.

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▼ **EUCALL participants at the first annual meeting at HZDR in 2016.**

EUCALL stimulated a strong engagement among different aspects of the various advanced light sources, not only in research and technical development but also in innovation and facility operation. EUCALL's work on harmonizing the overlap between accelerator-based and laser-based light source facilities has not only helped those facilities better meet the needs of their user communities, but also the project has provided a template for future research infrastructure clusters.

Regarding long-term strategies and research policies of research infrastructures in Europe, EUCALL's success proves that a well-defined cluster of complementary facilities—bringing people from different research areas to work together on common projects—is a highly effective method to address issues that are relevant across the European Research Area. New research infrastructures can especially benefit from these clusters, as the connections made with more established facilities help define best practices early on. These sorts of projects require additional resources, and future projects should help facilities collaborate in this way. Even as large research infrastructures and networks continue to be built and develop across Europe, all with specific goals and aims, it is critical for all of them to connect and collaborate on areas of common interest.

Beyond the end of EUCALL's Horizon 2020 funding period, the scientists involved have agreed to maintain their collaboration by establishing the "EUCALL Forum", which will include regular meetings and a continuation of joint research and networking activities. This ensures that EUCALL's successes will translate into sustainable collaborations between accelerator- and laser-based advanced light sources, to the continued benefit of all involved.

IMPRINT

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