European Laser Science and Technology Landscape and Roadmap

A joint report produced in cooperation between Laserlab-Europe and ELI


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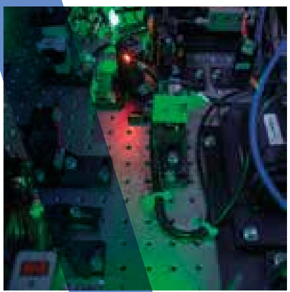
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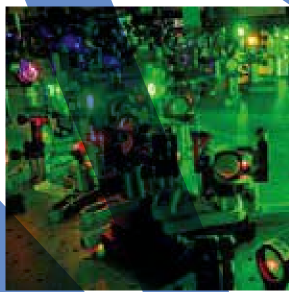
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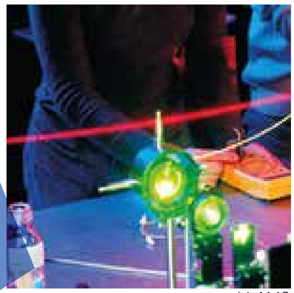
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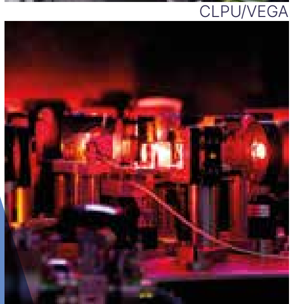
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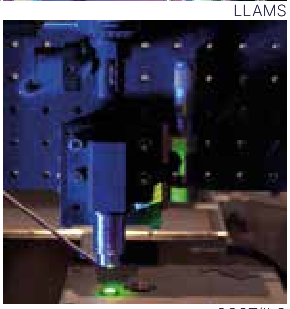
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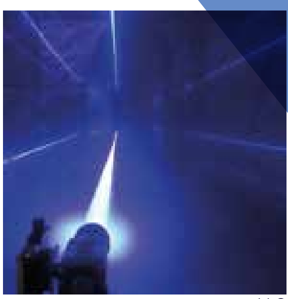
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ELI ERIC

Foreword

Laserlab-Europe and the Extreme Light Infrastructure European Research Infrastructure Consortium (ELI ERIC) have joined forces to analyse the current laser-based science landscape in Europe. This analysis aims to broadly qualify and quantify the European laser community to provide a better understanding of: the services offered to users by Research Infrastructures (RIs) operating laser sources, today and in the short- to medium-term future; and the user needs and requirements.

The consolidated report gives an overview of the complex landscape, identifies complementarities and efforts to be aligned, and defines high-level objectives. It provides data for European-level political consultations, where the importance of national RIs may be sometimes overlooked in view of the focus on ESFRI RIs and ERICs. Further, the factual and up-to-date information provided will support any discussions – with the European Commission and with national agencies – about sustainable funding for RIs.

Laserlab-Europe unites 46 leading organisations in laser-based interdisciplinary research from 22 countries. Its main objectives are to maintain a sustainable interdisciplinary network of European national laboratories, strengthen the leading European role in laser science, and offer access to state-of-the-art laser research facilities for cutting-edge experiments in a large variety of interdisciplinary research. Laserlab-Europe has received funding through a series of European Framework Programmes, including – currently – the European Union's Horizon 2020 research and innovation programme, under grant agreement no. 871124.

The Extreme Light Infrastructures (ELIs) – ELI Beamlines in Czech Republic and ELI ALPS in Hungary, under the unified governance of the ELI ERIC, and ELI-NP in Romania – house complementary record-breaking high-power, high-repetition-rate laser systems. As international user facilities dedicated to multi-disciplinary science and research applications of ultra-intense and ultra-short laser pulses, they provide access to the most diverse collections of advanced laser-based endstations, facilitating cutting-edge research and breakthrough technological innovations.

The present landscape analysis is a deliverable of the IMPULSE project (Integrated Management and Reliable Operations for User-based Laser Scientific Excellence), which is focused on achieving a quick and effective transition of ELI from construction into sustainable, unified operations. The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 871161.

Executive Summary

SYLVIE JACQUEMOT
Laserlab-Europe Project Coordinator

ALLEN WEEKS
ELI ERIC Director General &
IMPULSE Project Coordinator

JENS BIEGERT
Laserlab-Europe AISBL Executive Director

This European Laser Science and Technology Landscape and Roadmap report details the findings of a joint analysis conducted by Laserlab-Europe and the Extreme Light Infrastructure ERIC.

The analysis aimed to provide: an overview of the European laser community; a better understanding of the services offered by the Research Infrastructures (RIs) and of user needs; and data for political consultations at the European level.

The analysis methodology used a "think-tank" approach, along with two surveys. The first survey targeted laser RIs to gather information on the services offered, while the second survey targeted the user community to identify their needs.

Findings

The European laser RI landscape encompasses a diverse range of services – from primary to secondary sources covering the electromagnetic spectrum from x-rays to THz, and including particle sources – with a wide variety of instruments and techniques available to complement these various sources. Access to RI facilities includes dedicated support and expertise from local teams. Collaboration and support from technical and scientific teams are essential and highly valued by the user community.
The impact of laser-based instruments is broad, and crosses a large number of sectors.

- In the energy sector, lasers are contributing to the development of clean energy technologies, such as solar cells, smart materials, and laserdriven fusion. Further developments in this sector in Europe are needed to secure a sustainable and economic environment.
- In the health sector, lasers have long had a major impact, revolutionising for instance eye surgery and treatment. Today, they are increasingly being used in photodynamic therapy and for in vivo diagnostics, while laser-accelerated ultrashort secondary sources have the potential to change the landscape of radiation oncology.
- In space, applications include planetary exploration, global positioning and monitoring of the environment, laser orbital debris removal, and communications.
- For the environment, lasers are being used for the sensitive and accurate detection of environmental pollutants and microplastics. They are also proving essential in improving meteorological predictions and climate models, and for tracking livestock.
- In manufacturing, lasers can lead to a significant reduction in the use of chemicals, in energy consumption and in the production of hazardous waste.
- In food production and processing, lasers provide non-destructive methods for quality control and the security of food items.
- In cultural heritage, lasers are playing a significant role in the study and protection of cultural heritage artefacts, exploiting several non-invasive techniques. For instance, photoacoustic imaging has been used to image preparatory underdrawings, and laser-induced breakdown spectroscopy is being used for surface cleaning to preserve art.

Recommendations

The survey results suggest a need to establish a sustainable European laser RI ecosystem, offering improved access to facilities and increased collaboration. The challenges in standardisation, coordination and funding need to be addressed to ensure the sustainability and global competitiveness of the resulting ecosystem.

The report makes several recommendations to address these challenges, including:

- establishing a common strategy for laser RIs in Europe to better align efforts, enhance complementarities and increase synergies
- encouraging standardisation and interoperability of laser RIs to improve efficiency, facilitate user mobility and ensure data compatibility
- securing long-term and sustainable funding for laser RIs to ensure their stability, growth and competitiveness
- enhancing coordination between laser RIs and user communities, to gain a better understanding of user needs and requirements, and to better align the development of laser RIs with user demands.

Conclusion

This report provides valuable insights into the European laser RI landscape, its strengths and its challenges. By highlighting the importance of collaboration, standardisation, coordination and funding, it provides a solid foundation for the development of a strategic roadmap for the future of laser RIs in Europe. The findings and recommendations presented in the report will prove valuable to decision-makers, stakeholders and the wider laser RI community in ensuring the growth and sustainability of this critical field.

Introduction

Since the first working laser was operated in 1960, lasers can now be found everywhere in everyday life, in living rooms, supermarkets, medical offices and factories. In research laboratories, they are indispensable in many disciplines.

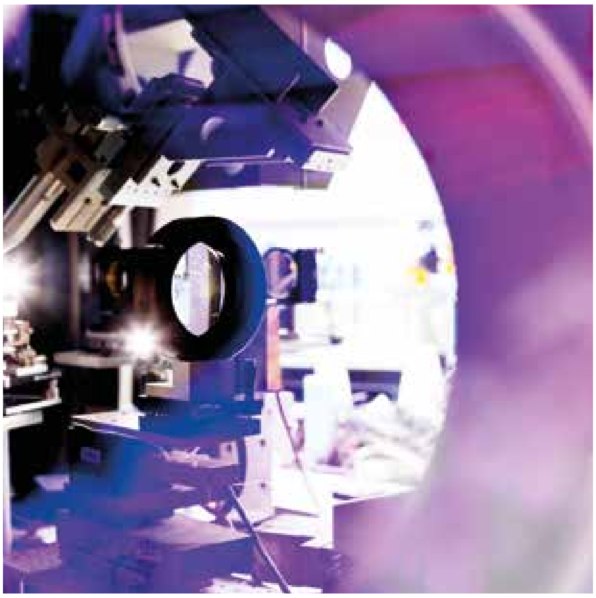
EP/LULI2000

Laser research infrastructures (laser RIs), offering energy, duration, repetition rate or spectral coverage far beyond that of laboratory-scale, play a major role in advancing laser science. To maintain Europe's leading position, future strategic scientific, technological and innovation-related challenges with regard to laser science, technology and applications must be addressed in a timely manner. To achieve this, a strategic roadmap needs to be established to guide the development of European laser RIs, from major upgrades of those currently operational to the commissioning of brand new facilities. Prior to this, an accurate analysis of the existing landscape is needed to establish the current position and, where possible, include the global perspective.This report aims to contribute to both of these exercises.

Our impact is driven by the success of our users

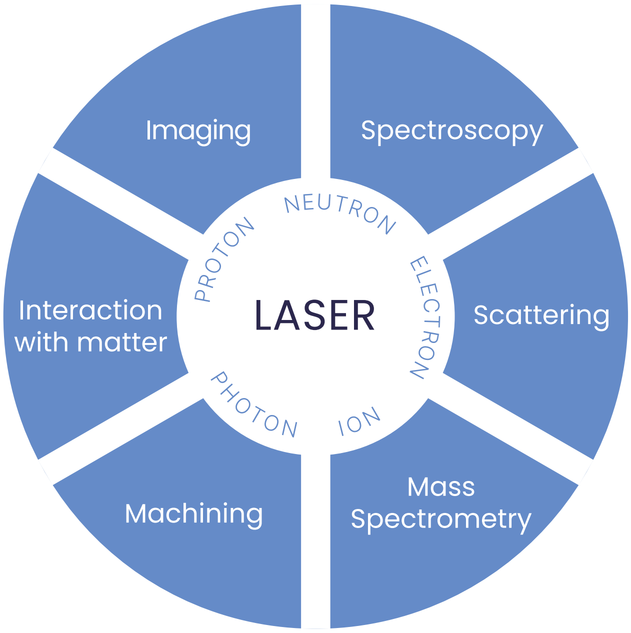
Methodology

To conduct the laser RI landscape analysis, a comprehensive methodology was developed, involving the creation of a think-tank and two surveys.
The think-tank was composed of representatives from ELI ERIC, Laserlab-Europe and the user community. To ensure that the laser RI community be adequately represented and avoid any bias, this composition took into account the scientific field of expertise of the members, as well as the size of their access-providing home RI.
The first survey targeted laser RIs to get a better understanding of the services currently being offered to users and how these services will evolve in the near to medium term. It was sent to all Laserlab-Europe members, the three ELIs, eight free-electron lasers (FELs) – members of the League of European Accelerator-based Photon Sources (LEAPS) – and facilities of national significance, either suggested by the Laserlab-Europe National Contact Points or identified on national RI roadmaps. For inclusion, facilities had to be currently operational and open (at least partly) to external users. Some RIs that will be commissioned in the near future were also approached, so that they could be included in the laser road-mapping exercise. The full list of the responding RIs is given in Annex I.
The second survey targeted the Laserlab-Europe user community, as well as the collaborators and potential users of the ELIs, given that the survey was launched before the first ELI call for proposals. The survey was designed to identify user needs, an important factor in the development of a laser RI roadmap, to ensure the future European laser RI ecosystem is both suitable and effective.



Collection François Lacour

Current Landscape of Laser Research Infrastructures in Europe



Diversity of the laser RI landscape

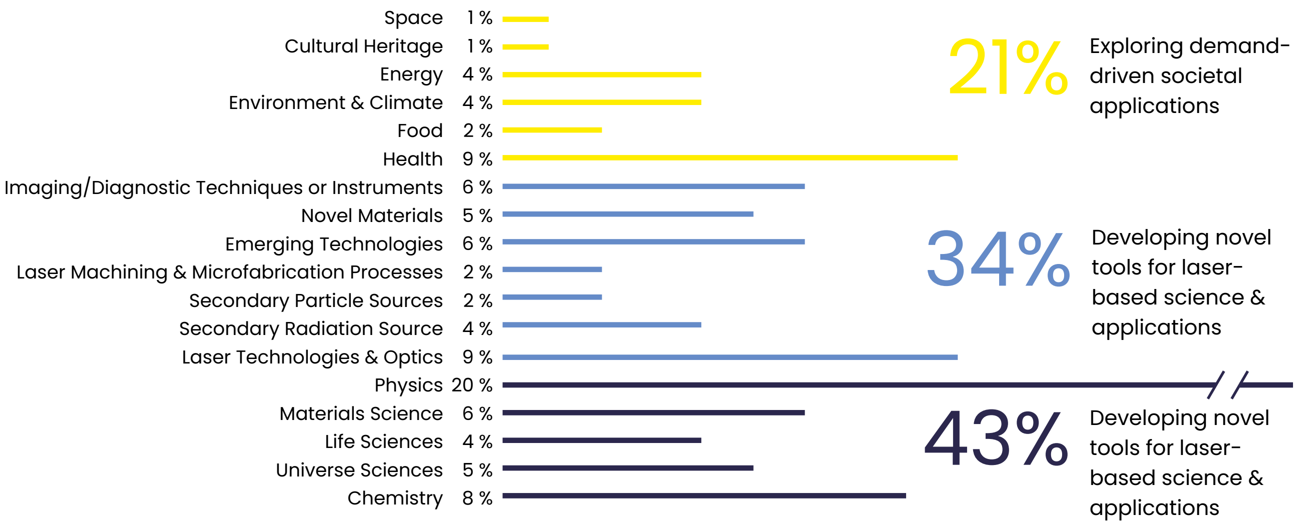
The RI survey revealed that the European laser landscape is extremely diverse in terms of the services offered to users, and is not restricted to laser photon providers. The services range from primary laser sources to secondary sources[1] – covering a wide range of radiation wavelengths and elementary particles – and include a variety of laser-based instruments and techniques.

A strong collaborative component exists alongside this access to tools and techniques. The majority of the RIs offer the support and expertise of their local technical and scientific teams, meeting the needs of almost 90% of users surveyed.

In addition, many RIs offer additional support services, which are greatly appreciated by users. For example, around half of the RIs offer mechanical workshops, one-third offer biology/cell culture laboratories (up to biosample management and handling) or target laboratories[2] , and one-fifth offer cryogenics. These additional features should be duly advertised, as they may be specific to the European laser RI community and they may encourage new users to apply for access.

There is also diversity in the scientific fields explored and the work undertaken, ranging from deepening fundamental knowledge in chemistry, the life sciences, physics, materials science and laboratory astrophysics/chemistry, to exploring societal applications for health, energy, cultural heritage, food or environment, through developing innovative laser-based tools and technologies.

[1] The term "secondary source" designates a source of radiation or a beam of particles produced after interaction with the matter (whatever its state) of a laser light source (thus referred to as the primary source).
[2] The concept of targetry covers not only solid targets, usually required for laser-matter interaction, but also gas/cluster/liquid jets, chemicals, phantoms, etc.



Percentages may not total 100 due to rounding.

The survey results indicate that RIs offer topical, comprehensive support across all these areas, although health projects are prioritised in some cases, as are projects that will future-proof RIs, especially the development of novel laser technologies and instrumentation tools, and of secondary sources for further applications.
The applications mentioned above are highly interdependent: the research activities hinge on knowledge accumulated in fundamental scientific disciplines and on the development of suitable technologies and tools to tackle successfully societal applications. For instance, environmental and medical applications are embedded in a very intricate landscape that connects different scientific disciplines (such as Life Sciences and Materials Science, or Life Sciences and Chemistry) and technologies (especially those designed to optimise secondary sources).

Such a complex panorama underlines the benefits of building a widespread, multidisciplinary network of instruments offering a multiplicity of services and laser source parameters.
Across Europe, there is a wide distribution of laser RIs hosted by some 23 countries, including 11 'Widening countries'.

These very diverse facilities – ranging from microscopy stations to highly accessible national instruments, to ESFRI landmarks and world-class infrastructures – each offer unique, high-quality services and expertise, and help to serve a broad user community extending beyond the European borders (around 10% of Laserlab-Europe's individual users are non-European). They also contribute to a coherent, staged laser ecosystem, coordinated in the main by Laserlab-Europe and ELI ERIC. The added value of such a multi-scale ecosystem has been demonstrated in pilot studies, where smaller facilities have fed projects through to large-scale ones to enable cutting-edge frontier science.


LASER FACILITY
FREE-ELECTRON LASER FACILITY
LASERLAB-NSC
U. Strathclyde/ SCAPA
QUB/TARANIS
LASERLAB DK
LLC
MAX IV
U. RIGA/LASER CENTRE
VULRC
EUROPEAN XFEL
DESY/FLASH
DESY/CFEL-ATTO
CLF
ORION
LASERLAB
FELIX
AMSTERDAM
MBI
MUT-IOE
PolFEL
MULTI-NANO
HIJ
IPHT/LPI
HZDR/ELBE
ELI Beamlines
HiLASE
PALS
IJCLAB/LASERIX
ISMO
LOA
LULI
LIDYL
CLIO
GSI/PHELIX
CALA
MPQ
ILC
SwissFEL
SMARTLIGHT
LACUS
Wigner RCP/FEMTOLAB
IEP-TU Graz/ NanoESCA
ELI ALPS
USZ/TeWaTi
USZ/HILL
LMJ-PETAL
CELIA
ILM/X-2M
CUSBO
FERMI
NFFA-Trieste
CALT
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CLUR
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ICFO
ILIL
LENS
ENEA/ABC
SPARC_LAB
HEPHAESTUS
SOFIA U./FSLAB
STAR
ULF-FORTH
IPPL

Capitalising on complementarities and synergies to achieve integration

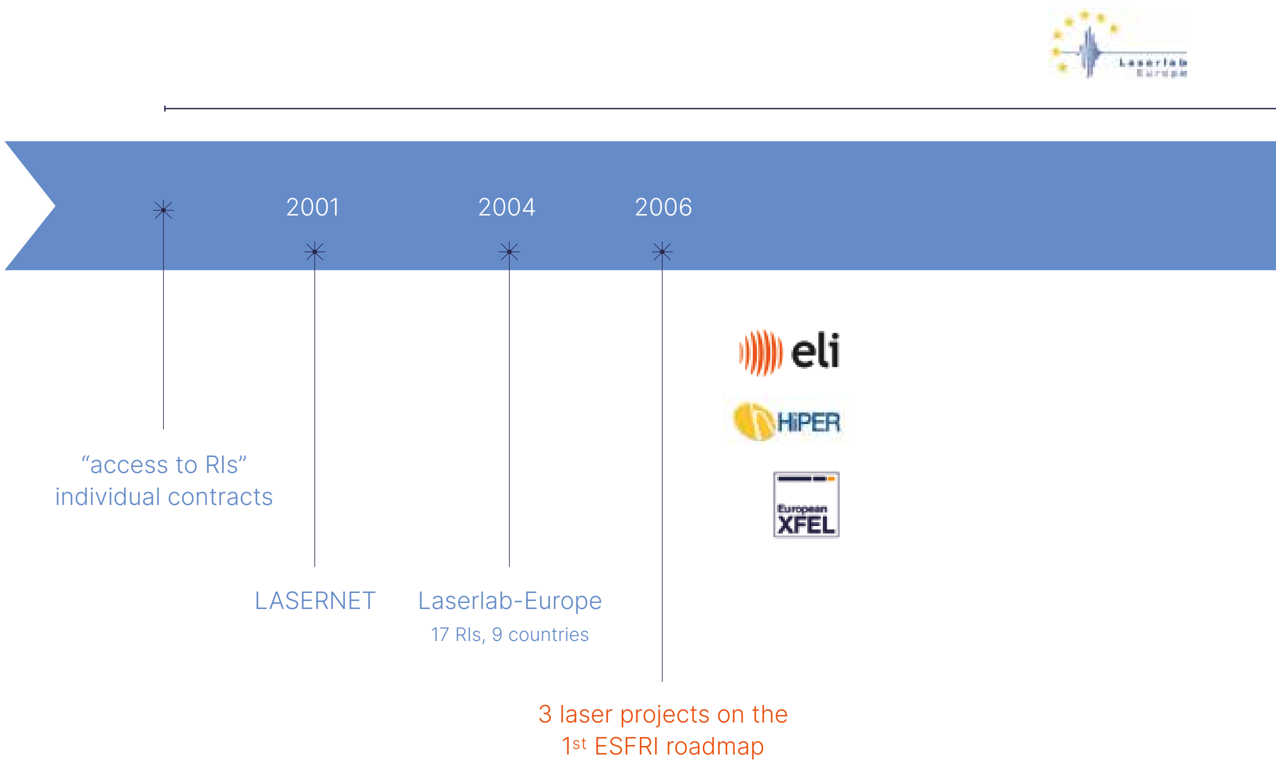
The European laser landscape is in constant evolution, with the situation changing to capitalise on the complementarities and synergies that exist to provide a collaborative, standardised and coordinated network.

Since the early 2000s, there has been movement from single entities that provided access under individual contracts, through a network (LASERNET) designed to reduce fragmentation, to a European Distributed Infrastructure that sits above national facilities, namely Laserlab-Europe. This consortium has progressively expanded from 17 to 46 partners to offer the user community access to an ever-broader spectrum of capabilities with, for instance, inclusion of free electron lasers (FELs) since 2015. Along this route, the preparatory phases of two pan-European very large-scale RIs, HiPER and ELI, have been supported. Laserlab-Europe has also gained sustainability with the establishment of the Laserlab-Europe AISBL in 2018.

The next step, following this landscape analysis, will be to engage in further integration. Once lasting transversal collaborations have been established with the ELIs, the ambition is to form a multi-scale laser consortium, followed by clustering with other analytical RIs.

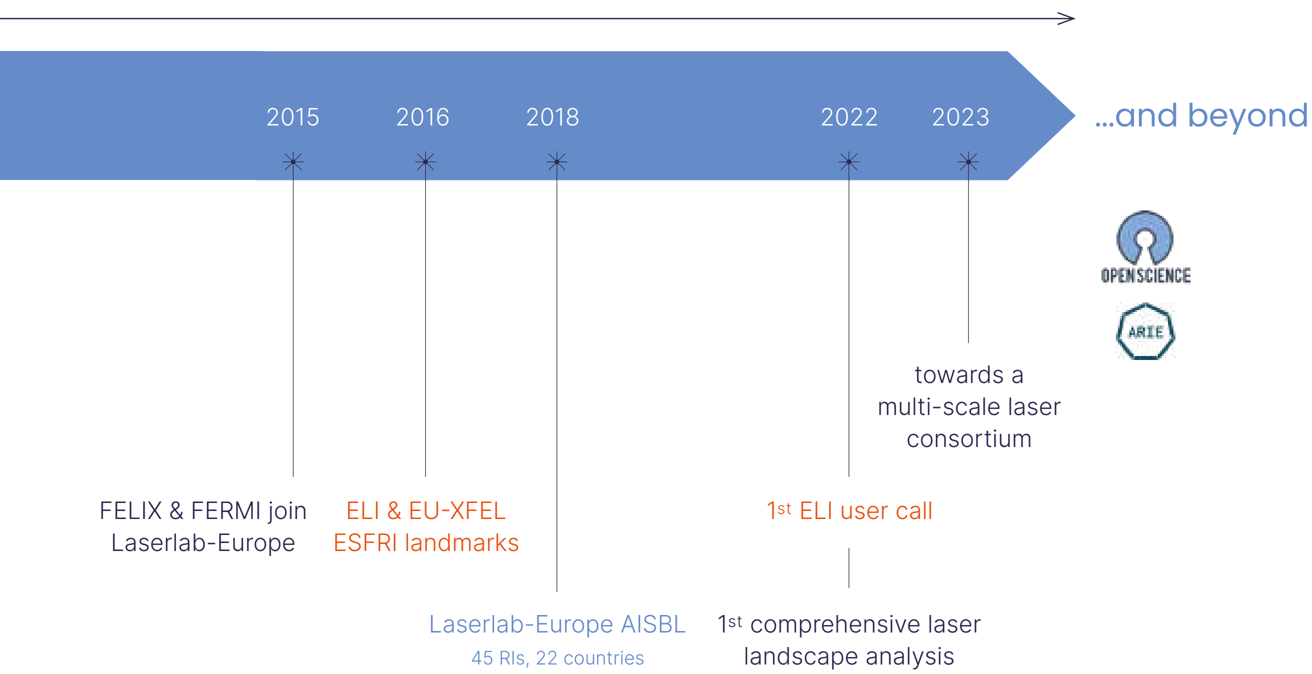
The ultimate transformation of the landscape will require all partners at all facilities to adopt the Open Science tenets. This step will require the implementation of common regulations on ethics and professional integrity, the development of suitable tools, and – possibly – the modification of current scientific routines.

Partners will need to accept these transformations; it is thus important that the necessary changes are progressively implemented and that the benefits that they will bring are effectively promoted and supported at the consortium level.



International context

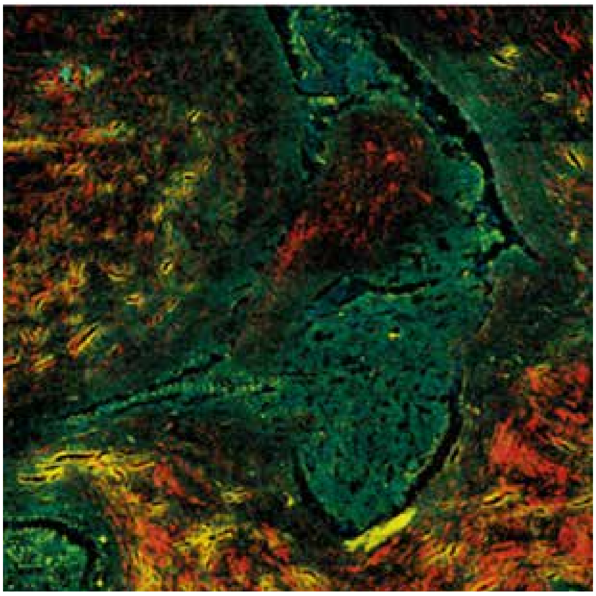
Focusing on the ultrahigh intensity component of the European laser RI ecosystem, it is worth mentioning that it represents the highest concentration of such facilities worldwide[3] and that it is largely able to support the market, which is expected to be worth around 15 billion euros by 2024.
However, strong competition for this market exists worldwide.
Following a 2017 report stating that the United States of America had lost its dominance in the field of high-intensity laser technology, the U.S. Department of Energy (DOE) established LaserNetUS, using Laserlab-Europe as a model, to improve the country's competitiveness in high-intensity laser research. The USA has also heavily invested in facility upgrades and user support (some $18 million over three years, from 2020). The ZEUS laser system at the University of Michigan has been funded (to bring the USA into the multi-petawatt world), along with an upgrade to the "Matter in Extreme Conditions" instrument at the Linac Coherent Light Source (LCLS), to increase its performance well above that of the equivalent "High Energy Density" instrument at the European XFEL.
In Asia, the laser facility at the Korean Center for Relativistic Laser Science (CoReLS) achieves the highest laser intensity globally and exawatt laser projects are underway in China, Japan and Korea, challenging the European supremacy.
As a result of opening the Laserlab-Europe programme to non-European users, and of the subsequent collaboration policy with the LaserNetUS and Asian Intense Laser Network (AILN) that lead to the reciprocal opening of their calls to the European community, users can select from all worldwide facilities to conduct their research. An increasing tendency of European users to conduct research outside of Europe was observed before the COVID pandemic, and is likely to be confirmed in the forthcoming years; if confirmed, the European laser RIs will need to work to maintain their competitiveness, for example by reinforcing the access to unique capabilities, such as those offered by ELI.



[3] See for instance the map drafted by ICUIL, the international committee on ultra-high intensity lasers (https://www.icuil.org/activities/laser-labs.html)

Laser Research Infrastructures helping Europe tackle global Challenges

The multiple facets of the European laser landscape are a major asset in helping Europe tackle global challenges.. The services offered, and the fields of research tackled by the user community and supported by the RIs, foster cross-disciplinary work and facilitate the emergence of new ideas and breakthrough innovations. Whatever transformations the laser landscape may undergo in the future, laser technology is already proven to be a game changer in many scientific, technological and societal areas.



Non-linear microscopy group, IESL-FORTH

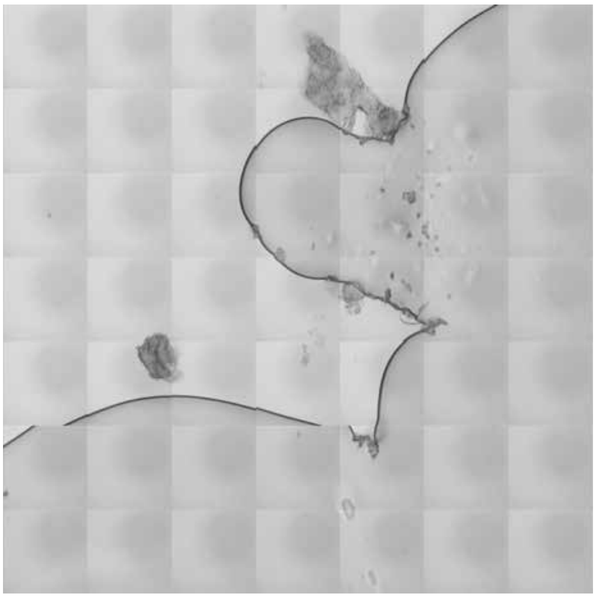
Environment

Environmental concerns can be addressed with the sensitive and accurate laser detection of atmospheric pollutants (such as soot from biomass burning or engines) and microplastic pollutants. An innovative microscopy approach that provides rapid identification of the major types of polymer particles has been successfully demonstrated on sediments from the Rotterdam harbour area, while fluorescence imaging has proven that algae can be used to monitor water quality, tracking pH modification to heavy metal presence. Laser diagnostic techniques also enable the temperature and species concentration in combustion systems to be measured, contributing to their optimisation to reduce emissions; it has been shown that it is possible to monitor – in real time – the toxic organic by-products (such as dioxins) of incineration processes to enable fast counteractions.

Health

The capability of multimodal non-linear laser-based microscopy techniques to discriminate benign from cancerous samples within seconds has been demonstrated, far quicker than a surgical procedure. As with other imaging modalities, these techniques promise non-invasive diagnostic tools for reducing recalls and unnecessary biopsies, or for providing instant feedback on the nature of an excised tissue. Polarisation-sensitive optical coherence tomography imaging has been shown to be a promising, minimally invasive diagnostic method to assess asthma-induced airway remodelling. Photoacoustic tomography is an emerging technique providing label-free non-invasive 3D structural and functional images of, for example, vascular systems. More generally, laser-based in vivo diagnostic techniques are proving simpler and cheaper than current traditional techniques; they complement these latter usefully, providing objective (op-erator-independent) functional information.

While photodynamic therapy is now being widely used to treat many conditions (including acne, several cancers, psoriasis, etc.), laser-accelerated ultrashort secondary sources may also change the landscape of radiation oncology, taking advantage of unprecedented instantaneous high dose rates (of the order of gigagray/s) delivered on sample. Recently, an important milestone was achieved, with the first-ever controlled in vivo irradiation of mice tumours with laser-accelerated protons, which showed a clear radiation-induced effect.



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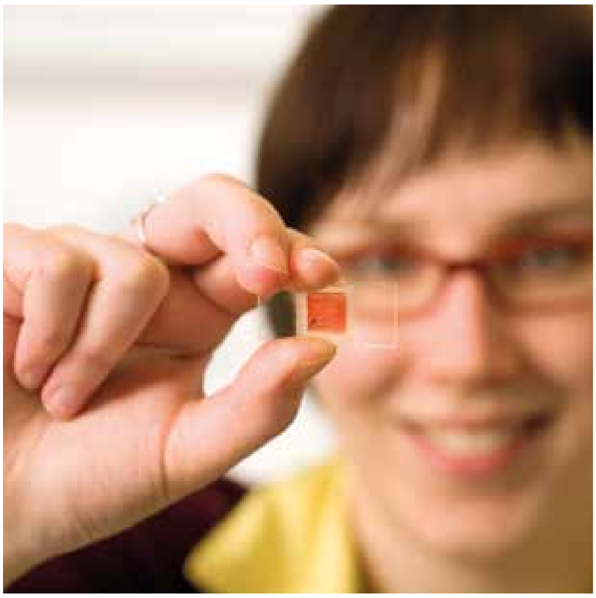
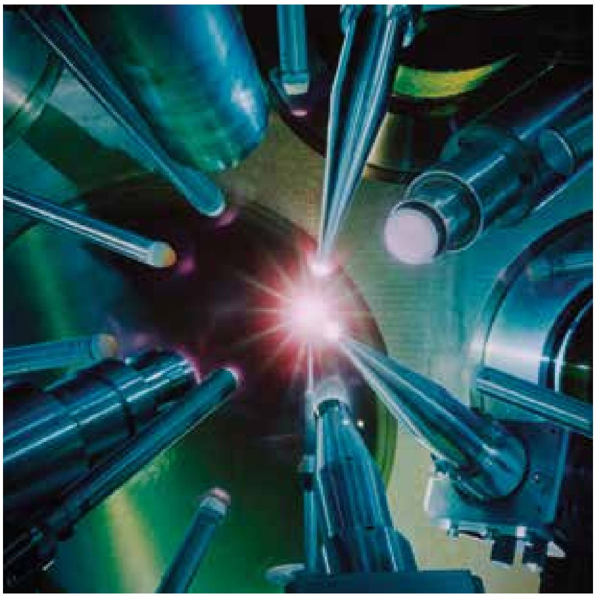
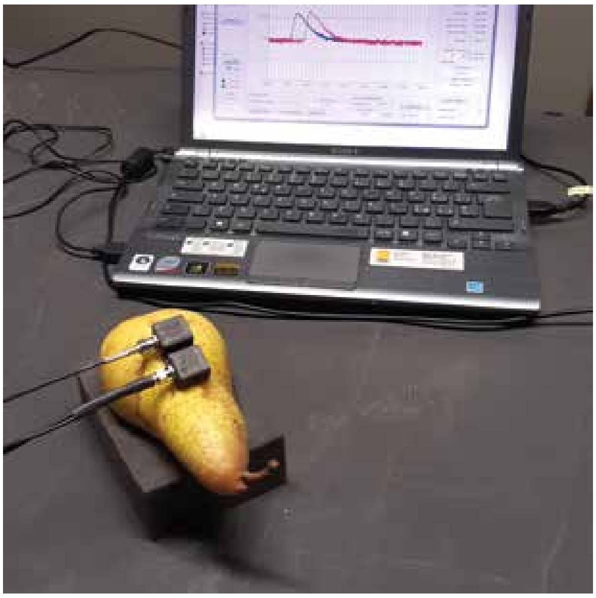


Nanoscience Center/ University of Jyväskylä, Petri Blomqvist



Lawrence Livermore National Laboratory



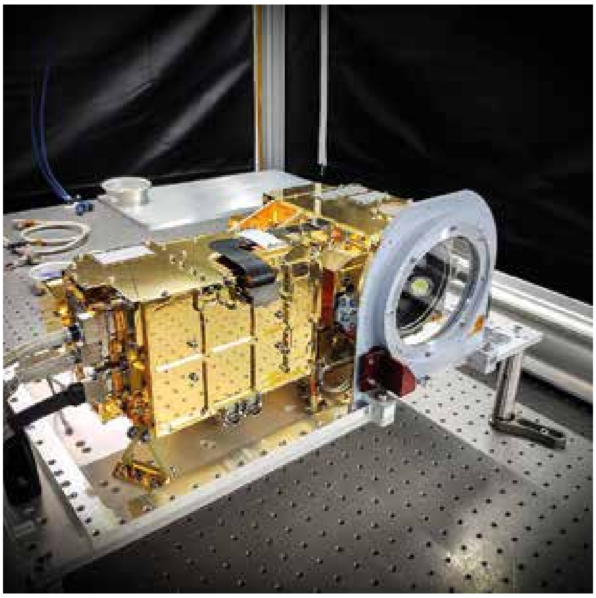
POLIMI

Food

Lasers form the basis of several non-destructive methods used for a variety of applications to ensure healthy and high-quality food items. For example, a technique has been developed to provide in-line quality control of packed food items throughout the supply chain through the non-invasive measurement of the oxygen content in the packaging headspace (which needs to be kept to a minimum). With laser techniques, it is also possible to analyse the protein content in wheat flour, a key nutritional element, or to predict fruit maturity and ripening for which recent advances allow the design of portable instrumentation for use in the pre-harvest (i.e. in the orchards) and post-harvest.

Energy

Lasers are also widely contributing to the development of clean energy technologies, among them solar energy, smart materials and laser-driven fusion. They can provide valuable insights into the fundamental processes occurring at ultrashort timescales in solar electricity generation, such as charge transfer processes in dye-sensitised, organometal halide perovskite solar cells, and help to identify the best possible materials to be used. Novel ultrafast coherent radiation sources are of special interest as they allow the probing of very small (at the sub nanometre scale) structural changes. Lasers can be used to functionalise materials thanks to multi-dimensional nanostructuring: this may benefit energy storage, for example through the development of nanostructured electrodes for more efficient hydrogen production devices, fuel cells or batteries. Similarly, new quantum materials with the potential to reduce the energy consumption of consumer electronic devices can be investigated with ultrafast laser techniques.
Laser-driven fusion is seen as a potential clean and safe energy source for the future, especially after recent achievements at the National Ignition Facility(NIF) in the USA. Further scientific and techological developments are still required to transform NIF's results into power production. While existing laser facilities will allow the development – at a reduced scale – of ideas for advanced energy-suitable ignition schemes (such as shock ignition, on which the preparatory phase of the ESFRI HiPER project was finally focused), a new full-scale facility, based on innovative high-energy high-repetition-rate laser technologies and low-cost target technologies, is required to demonstrate the feasibility of laser fusion energy. Considering the cost of such a facility, a trans-national coordinated effort will be needed, as has been achieved by the magnetic fusion energy community with the ITER programme.



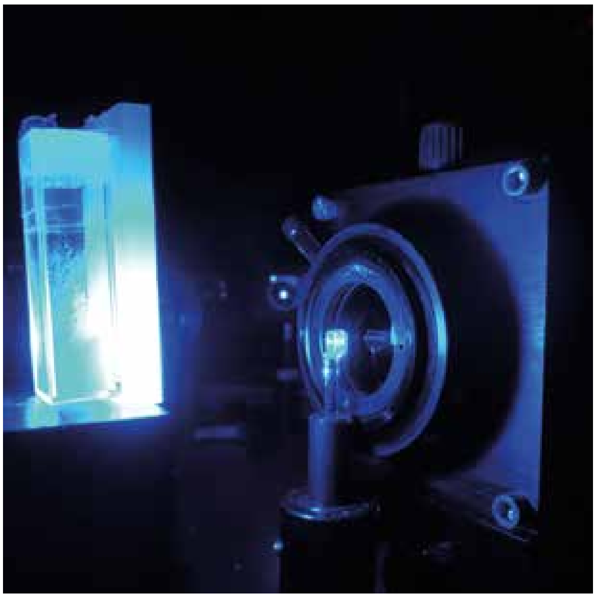
ESA

Space

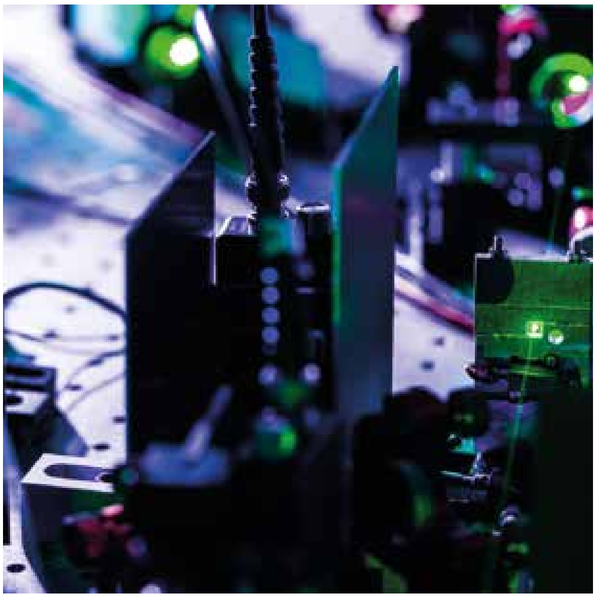
Lasers are beginning to be widely used in space applications, including laser guide stars in astronomical adaptive optics systems, to correct atmospheric distortion of light, and laser-based frequency combs to find exoplanets. Optical technologies and lasers are being used to power atomic clocks for global positioning, to monitor the environment, and for international communication. They are also useful for planetary exploration, such as LIBS coupled to Raman spectroscopy for the SuperCam instrument on board the Perseverance Mars Rover, allowing the investigation of the elemental composition of soils and rocks and the search for bio-signatures.
Space debris threatens the use of the low Earth orbit space; removing it, whatever its size, is therefore an urgent issue. A series of concepts has already been proposed, among them laser orbital debris removal. The laser parameters required to de-orbit or ablate the debris from ground or from space are still being determined, through laser-matter interaction experiments being conducted through access to laser RIs. The first step, which involves tracking the debris very precisely using laser pulses, has been taken with, for instance, ESA's IZN-1 Laser Ranging Station.
Laser communication in space is now widely used from satellite to satellite, allowing more data to be packed into a single transmission, but effort is still needed to solve the engineering challenges (e.g. laser beam distortion due to atmospheric effects) to be able to employ it from satellite to the ground station since the first demonstration by Japan in 1995.

Safety and security

Lasers contribute to global security and forensics. Laser-based spectroscopy techniques can be used to non-invasively detect the presence of dinitrotoluene, a material found in many explosives, through layers of non-transparent diffusively-scattering plastics, while proton radiography is capable of detecting thin layers of low-Z material behind high-Z shielding.



Maria Lopez-Lopez



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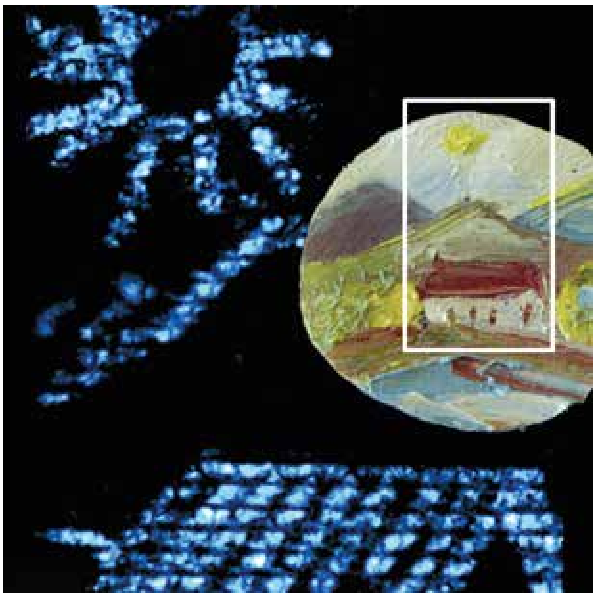

[adapted from Sci. Rep. 7, 147 (2017)]

Culture

Thanks to the wide range of non-invasive techniques they enable, lasers play an important role in the study and protection of Cultural Heritage artefacts, from ancient coins to medieval gemstones to invaluable paintings. For instance, the unique capabilities of photoacoustic imaging have been exploited – under controlled laboratory conditions – to image preparatory underdrawings, while photoluminescence microscopy has been used to identify synthetic semiconductor pigments and investigate related degradation phenomena. LIBS is also being used for surface cleaning to preserve art, for instance the west frieze of the Parthenon in Athens.

Industry

European RIs have contributed to the understanding of the physics of laser-produced radiation sources for EUV lithography. The latest 250 W machines at wavelengths near 13.5 nm are based on the interaction of a high-average-power laser with tin droplets, capitalising on years of fundamental research in plasma physics. The next generation of machine (which will aim to increase throughput at shorter wavelength (6.7 nm) or higher power (kW), and decrease electrical energy consumption) is under development. Compact XFELs are among the possible driver candidates.

Laser manufacturing is at the basis of another game-changing technology, namely additive manufacturing (or 3D printing), which has a wide range of applications, in biomedicine, for embedded electronics, etc. With metals, post-processes to improve the fatigue behaviour of aerospace or medical products are currently being developed to, for example, induce compressive residual stresses deep in the material and thereby increase resistance to crack initiation. A novel route combining laser lithography and thermal post-treatment was developed in parallel to enable additive manufacturing of crystalline ceramics at unprecedented precision (below 60 nm) and 3D flexibility.

Lasers in manufacturing industry can lead to a significant reduction in chemical use, energy consumption and hazardous waste production. The replacement of traditional techniques with modern laser-based processing ones is, in addition, reducing surface contaminants and greenhouse gas emissions.

Laser technology is also extensively used in optical fibre communications, especially for transmitting information over large distances with low loss owing to lesser divergence, as well as in underwater communication techniques.

Needs and Gaps of the European RI Community

ELI ALPS

Supporting transformations and strengthening European competitiveness

[redacted]

A lot of development and support is still required to put the scientific potential of the laser technologies into practice. Above all, the three-pillar ecosystem of education, academia and industry needs to be consolidated.
To that end, it is necessary to gear training activities towards not only users, but also to students from universities and technological institutes in order to increase the human resources at the RIs.
It is worth mentioning that access to the laser RIs has a strong training component, with a user community mainly university-based and relatively young; for instance, more than half of the Laserlab-Europe users are under 37 years old. In addition, a global staffing strategy would rely on professional staff development at the European level, involving a range of activities from continuing vocational training to inter-RI staff exchanges or secondments.
External staffing processes, which are vital for RIs in the medium- to long-term, must of course factor in equality, diversity and inclusion.
Appropriate specialised training in areas with high industrial and societal impact should reinforce the ability of the RIs to innovate. Coupled to a rational expansion of local knowledge sharing and technology transfer policies, it will help to turn the innovative concepts developed in the labs into prototypes, paving the way to industrial products, which – in the end – will help to maintain European leadership.
Industrial access to the RIs is also a key component of European leadership. Over half of the RIs surveyed have already opened their facilities to industry or to medical centres, even where this does not fall under a standard transnational access activity, showing an industrial need for services such as optical metrology and material analysis using laser-based techniques, laser machining, and concept proofing of novel approaches or devices. Issues related to confidentiality and IPR management, transnationality, or fast access track, need to be addressed to support further industrial access; solutions may encompass a redefinition of the transnational access requirements (allowing SMEs to access local RIs within the laser consortium) or of the access concept (allowing not only access to services, but also to expertise).
It would be valuable to improve public awareness of laser technologies through targeted communication. Social studies indicate that people are eager to be find out more about some emerging applications of the laser technologies, such as laser fusion or nanobiomedicine. Communication activities shall be mainly conducted at the regional or national level, al-though adequate and efficient coordination and some financial incentives are needed at the European level.

Closing gaps and meeting targeted challenges

The actions described above are not sufficient to meet the challenges posed by the foreseen transformations, and to smoothly close the gaps between them and the current situation. The coordinated management of responses to European calls for proposals is essential to strengthen the role of RIs and to ensure the continuity of the RI services to users. The aim is not only to continue to provide support for transnational user access – with coordination at the European level – but also to set up a common procurement system for optics or other laser components (as suggested by the Laserlab-Europe Industrial Advisory Committee) for cost and benefit optimisation.

Securing supply chains of raw materials, as well as processing capabilities, will ensure that, for key laser and electronic technologies, Europe keeps its self-sufficiency vis-à-vis, for example, China and has the resources necessary to prevent future shortages. Such an action may require bringing relevant industries back to Europe; for example, beryllium ceramics or selenium-doped crystals are among the critical components not currently manufactured in Europe. Implementing material recycling chains across the RIs would also contribute to minimise tensions on external supply chains and improve sustainability.

Major R&D collaborative projects must be promoted at the laser consortium level – whatever it is – to benefit from complementarities and synergies. A number of priority axes have been identified, as described in the following paragraphs, and should be further investigated.

The need to operate more energy-effective laser systems and secondary sources is already apparent. Solutions will rely on the development of cost-effective diode-pumped laser sources, the search for new active laser materials and the improvement of the primary-to-secondary source conversion efficiencies (currently rather moderate, below 20% for instance for laser-accelerated proton sources). RIs may play a key role by specifying requirements in terms of laser parameters and enabling demonstration of new concepts.

Improvements in terms of efficiency are not only contributing to the carbon footprint of laser technologies, but also allowing the development of portable hand-held laser sources for operation in clinical environments. In addition to compactness, in vivo diagnostics require the development of tunable pulsed laser sources and reliable delivery systems, while entering medical markets necessitate that the laser systems be as cheap as possible. Reliability (i.e. stable and robust laser operation and delivery of reproducible laser pulses on sample) is in fact a common challenge for all high-average-power systems and an important user need, while broad wavelength laser tunability will also strongly benefit communication or remote-sensing applications.

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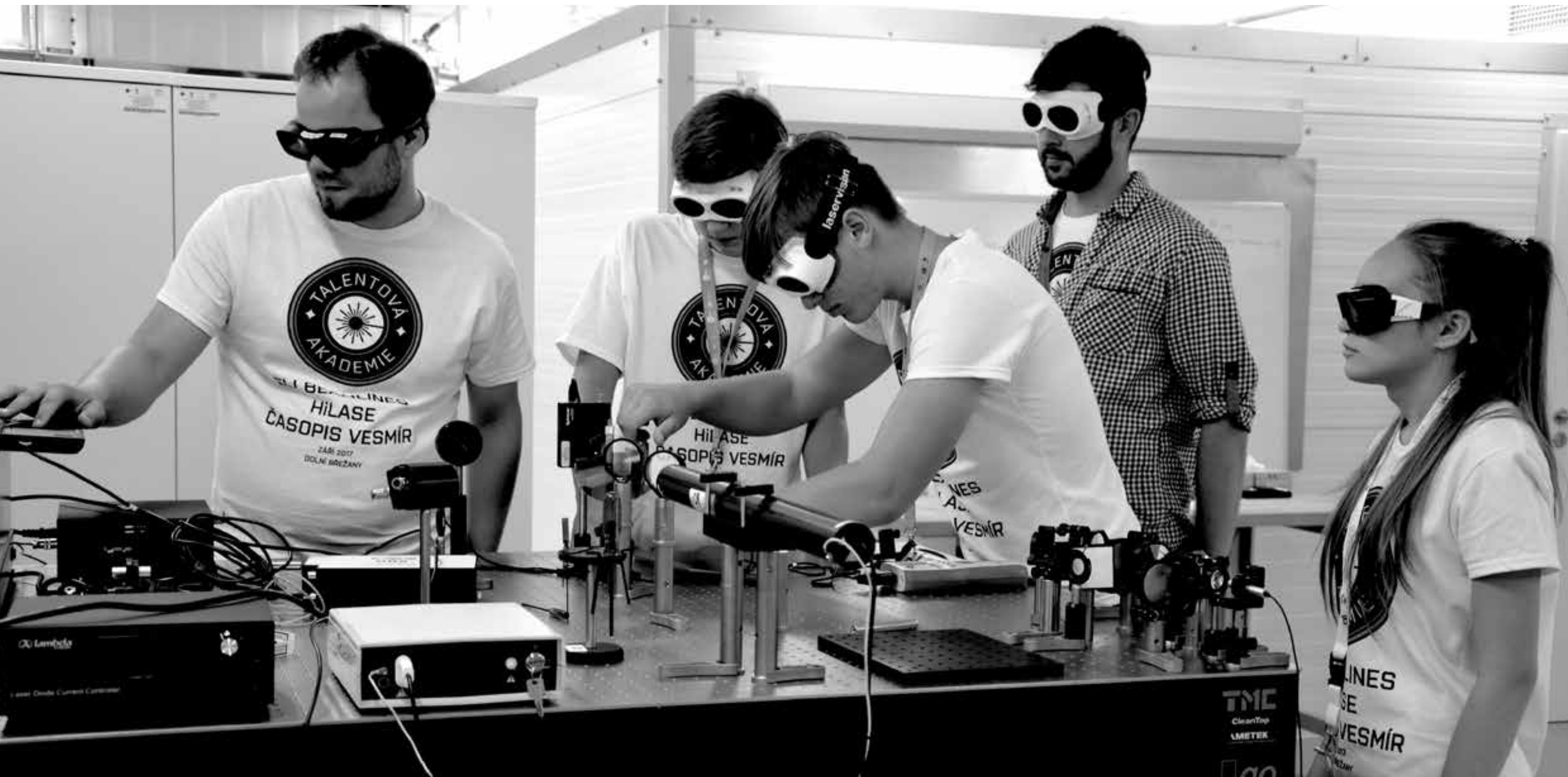
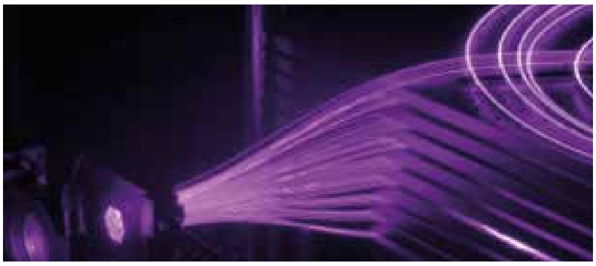


Other R&D activities to pursue and support include coherent beam combining to reach the highest energies or the highest powers, on-shot complete metrology of primary and secondary sources, using standardised protocols, and efficient data management and IT tools to withstand the highest repetition rates. The use of artificial intelligence (machine learning) shall be investigated, whether it be to optimise laser machining (cutting, welding, additive manufacturing) processes, to predict surgery outcomes or to design laser fusion experiments.

These R&D activities will gain valuable support through the creation of joint research units between companies and RIs, such as HERACLES3 between Thales, LOA and LULI in France, or through RI-industry co-developments.

The need for coordinated access to a variety of instruments or techniques (or to fully-integrated stations clustering laser sources, spectroscopy/super-resolution microscopy instruments, optogenetics techniques, models and in situ data analysis), and for the combination – on sample – of different light sources (for instance infrared laser plus free-electron laser pulses, laser pulses plus ion beams, laser pulses plus magnetic fields, laser pulses of different wavelengths or durations, etc.), was clearly identified in the answers to the user survey. Establishing such multi-in-strument access routes across the RI services could be the first step in a phased approach to clustering. An important step to bridge the gap between FEL and IR laser facilities was recently taken with the demonstration of seeded FEL lasing in the ultraviolet regime based on laser-plasma acceleration.



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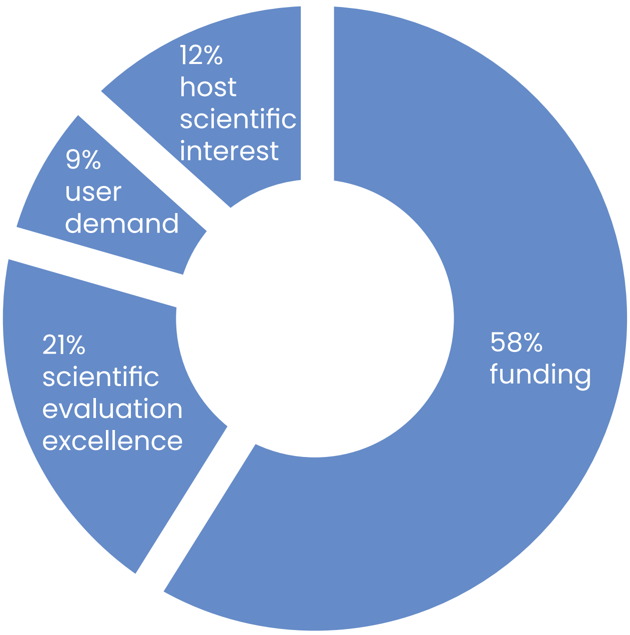
Co-funded access to RIs for research and innovation

Whatever the reason behind the access – multi-instrumental as defined above or curiosity-driven – the user community, as a whole, cites access to RIs as of the utmost importance for conducting excellent and innovative research. According to the survey, more than 70% of users are planning to reapply for access in the future, if support is obtainable.

Such a scenario needs to be examined alongside the RIs' aspirations and capacities. One question in the RI survey was dedicated to identifying the primary motivation behind providing access: the answers are reported in the side doughnut diagram. For more than half of the RIs, access opportunities are mainly determined by funding availability. Although hosting scientifically excellent projects is an important incentive, realistically it is not enough by itself. Therefore, if funding is available, RIs are ready to continue to support more transnational access, offering either more services to users or an increased fraction of beamtime, thus fostering first-rate European science. Such a rationale strongly supports specific funding requests. A majority of the RIs benefit from national or regional grants that finance operational costs and, up to a certain degree, national access. However, transnational access – which is at the heart of the excellence of European research – should continue to benefit from subsidies at the European level, not only to cover user travel and subsistence expenses, but also to contribute to keeping the RIs in widening countries at the forefront by triggering governmental initiatives.



In conclusion, ensuring the sustainability of RI services requires co-funding from a number of organisations, from regional or national bodies (for operation, short-term R&D and national access) to European institutions (for investments in new very-large-scale RIs or internationally-relevant upgrades, and for transnational access).

Annexes

Laser Research Infrastructures

The following table presents the list of the Research Infrastructures (RIs), which have been considered in the laser landscape analysis and road-mapping exercise, per country and per analytical order. It contains also information on their inclusion on ESFRI or national roadmaps (as of December 2022) and on any affiliation to European consortia.

Country	Name of the RI	ESFRI/national roadmap (if any)	Consortium (if any)
Austria	IEP-TU Graz/NanoESCA	Identified as a core facility in the Austrian RI database	Laserlab-Europe
Belgium	Multi-Nano	Large-scale RI in Flanders	-
Bulgaria	HEPHAESTUS	Bulgarian national research and innovation complex	-
	Sofia U./FSLAB	-	Laserlab-Europe
Croatia	CALT	Croatian national priority	Laserlab-Europe
Czech Republic	ELI Beamlines	ESFRI landmark as ELI ERIC	ELI ERIC
	HILASE	Mentioned as facility complementary to ELI in the Czech roadmap	Laserlab-Europe
	PALS	Czech large-scale RI	Laserlab-Europe
Denmark	Laserlab DK	Not currently (Danish Roadmap for RI 2011)	Laserlab-Europe
Finland	Laserlab-NSC	-	Laserlab-Europe

Country	Name of the RI	ESFRI/national roadmap (if any)	Consortium (if any)
France	CELIA	Mentioned as user-accessible facility in the French roadmap	Laserlab-Europe
	LMJ-PETAL	RI in the French roadmap	Laserlab-Europe
	CLIO	-	LEAPS
	IJCLAB/LASERIX	Mentioned as user-accessible facility in the French roadmap	-
	ILM/X-2M	-	-
	ISMO	Mentioned as user-accessible facility in the French roadmap	Laserlab-Europe
	LIDYL	ATTOLAB mentioned as user-accessible facility in the French roadmap	Laserlab-Europe
	LOA	Mentioned as user-accessible facility in the French roadmap	Laserlab-Europe
	LP3	Mentioned as user-accessible facility in the French roadmap	Laserlab-Europe
	LULI	APOLLON listed as large-scale RI (RI*) and LULI2000 mentioned as user-accessible facility in the French roadmap	Laserlab-Europe
	SMARTLIGHT	Funded in 2020 as national equipment platform	-
Germany	CALA	-	-
	European XFEL	ESFRI landmark	LEAPS
	DESY/FLASH	Helmholtz large RI	LEAPS
	DESY/CFEL-ATTO	-	Laserlab-Europe
	GSI/PHELIX	Identified as Helmholtz R&I facility	Laserlab-Europe
	HIJ	POLARIS identified as Helmholtz R&I facility	Laserlab-Europe
	HZDR/ELBE	Helmholtz large RI	Laserlab-Europe & LEAPS
	IPHT/LPI	Project of German national RI	Laserlab-Europe
	MBI	-	Laserlab-Europe
	MPQ	-	Laserlab-Europe
Greece	IPPL-HMU	Greek roadmap RI as HELLAS-CH	-
	ULF-FORTH	Greek roadmap RI as HELLAS-CH and INNOVATION.EL	Laserlab-Europe
Hungary	ELI ALPS	ESFRI landmark as ELI ERIC	ELI ERIC
	USZ/HILL	Member of the Hungarian laser-based RI group	Laserlab-Europe
	USZ/TeWaTi	Member of the Hungarian laser-based RI group	Laserlab-Europe
	Wigner RCP/Femtolab	Member of the Hungarian laser-based RI group	Laserlab-Europe

Country	Name of the RI	ESFRI/national roadmap (if any)	Consortium (if any)
Italy	CUSBO	Reported in the Italian PNRI 2021-2027	Laserlab-Europe
	ENEA/ABC	Reported in the Italian PNRI 2021-2027 as part of ENEA-CE-TRA	Laserlab-Europe
	FERMI	Reported in the Italian PNRI 2021-2027	Laserlab-Europe & LEAPS
	CNR/ILIL	-	-
	LENS	Reported in the Italian PNRI 2021-2027	Laserlab-Europe
	LFN/SPARC_LAB	Reported in the Italian PNRI 2021-2027 as part of INFN-LNF	LEAPS
	NFFA-Trieste/ SPRINT	Reported in the Italian PNRI 2021-2027	-
	STAR	Reported in the Italian PNRI 2021-2027	-
Latvia	ULLC	-	Laserlab-Europe
Lithuania	VULRC	Lithuanian RI as part of Laser RI	Laserlab-Europe
Netherlands	FELIX	Dutch large-scale RI as part of HFML-FELIX	Laserlab-Europe & LEAPS
	LLAMS	-	Laserlab-Europe
Poland	MUT-IOE	-	Laserlab-Europe
	POLFEL	Polish RI project	LEAPS
Portugal	CLL	Portugese RI as part of Laser-lab-Portugal	Laserlab-Europe
	IST/IPFN	Portugese RI as part of Laser-lab-Portugal	Laserlab-Europe
Romania	CETAL	-	Laserlab-Europe
	ELI-NP	Romanian RI of European rele-vance	-

Country	Name of the RI	ESFRI/national roadmap (if any)	Consortium (if any)
Slovakia	SCSTI/ILC	Listed as parner of the Slovak BioImaging Network	Laserlab-Europe
Spain	CLPU	Spanish Unique Science and Technology Infrastructure	Laserlab-Europe
	CLUR	-	Laserlab-Europe
	ICFO	Spanish Severo Ochoa Center of Excellence	Laserlab-Europe
Sweden	LLC	-	Laserlab-Europe
	Laserlab-Sweden	-	-
	Max IV	Swedish RI project	LEAPS
Switzerland	LACUS	Swiss institution-based station	Laserlab-Europe
	PSI/SwissFEL	Swiss national RI	LEAPS
United Kingdom	Central Laser Facility (CLF)	UK Research and Innovation Infrastructure	Laserlab-Europe
	AWE/ORION	-	Laserlab-Europe
	QUB/TARANIS	UK Research and Innovation Infrastructure	-
	STRATH/SCAPA	UK Research and Innovation Infrastructure	Laserlab-Europe

To facilitate the analysis of the laser RI landscape and identify commonalities, categories have been determined for the laser RIs according to the laser energy or the laser power (for CPA systems) currently delivered on sample, or soon to be delivered (funding for completion being available):

- very-large-scale laser facilities: more than 100 kJ (MJ-scale nanosecond laser pulses) or more than 1 PW (multi-PW-scale picosecond or femtosecond laser pulses)
- large-scale laser facilities: between 0.5 and 1 kJ (kJ-scale) or between 0.5 and 1 PW (PW-scale)
- mid-scale laser facilities: from 100 TW to 0.5 PW or from 100 J to 0.5 kJ
- small-scale laser facilities and stations.

The last two categories are grouping all the low energy and/or low-power laser facilities; a station does not give direct access to a laser source for laser-matter interaction experiments, contrary to a small-scale laser facility, but operate laser-based instruments, mainly microscopy, spectroscopy or imaging endstations.

Detailed information of the RIs listed above is given below per category, including key parameters[4] and the services – in terms of instruments or techniques – offered to users, if relevant; upgrades foreseen in the near future are also mentioned (in italic)[5].

Metrology tools for the primary sources, as well as for the secondary sources (such as spectrometers, Thomson parabolas, plasma diagnostics, etc.), are usually provided and not mentioned. Acronyms are defined in Annex II.

[4] Laser wavelengths are only mentioned when unconventional; for CPA Ti:sapphire systems, the central wavelength is ~800 nm, for Nd:glass systems 1.05 µm and for Yb:doped systems 1.03 µm.

[5] The ↗ or ↘ symbols indicate that the laser parameters preceding them are expected to increase or decrease to the subsequent values in the future.

Very-large-scale RIs

LMJ-PETAL (FR)	**LMJ-PETAL is the highest-energy, MJ-class, Nd:glass laser facility in Europe.** Coupling the Laser MégaJoule (LMJ: 330 kJ - 80 beams ↗ 1.3 MJ - 176 beams / 3 ns at the 3rd harmonic: 351 nm) and the Petawatt Aquitaine Laser (PETAL: 0.6 PW ↗ 1.4 PW / ~1019 W/cm2 / 0.7 ps) laser pulses at a repetition rate of 1 shot/day, it offers unique capabilities to study, thanks to a variety of plasma diagnostics (currently 21 ↗ 36) and to brilliant ultra-short radiation and particle sources, high-energy-density physics for applications in materials science, inertial fusion and laboratory astrophysics. An external magnetic field generator is under consideration and would allow the study of magnetised plasmas.

Soon-to-be very-large-scale RIs

Once these RIs will be completed, Europe's leading position will be reinforced with six very-large-scale laser RIs, representing more than 1 MJ of energy and roughly 60 PW of power.

AWE/ORION (GB)	**ORION** at the Atomic Weapons Establishment **is a large-scale multi-beam high-energy / high-power Nd:glass laser facility** designed to investigate laser-plasma interaction and high-energy-density physics, including laser fusion, and **allowing spherical target compression** in the ns regime (using flexible pulse shaping) plus additional target heating and diagnosis in the ps regime. Indeed, it couples on target ten 500 J / 1ns laser beams at the 3rd harmonic (351 nm) to two laser beams: 1 PW *↗ 3.7 PW / 500 fs and 400 TW ↗ 3.6 PW / 500 fs ↘ 150 fs*, this latter being at the 2nd harmonic (527 nm) for a better contrast. Five shots per day are delivered and a suite of plasma diagnostics is available to users. Academic access is arranged through the CLF.
CALA (DE)	The Centre for Advanced Laser Applications (CALA) houses two laser sources: ATLAS (CPA Ti:sapphire: 240 TW *↗ 3 PW* / 25 fs [1 Hz]) and PFS-pro (Petawatt Field Synthesizer - Yb:YAG OPCPA: 2.5 TW / 40 fs / 70-1400 nm [10 kHz]) to serve dedicated experimental areas and beamlines: LION (laser ion acceleration), HF (high-field physics), ETTF (electron acceleration and induced x-ray radiation). SPECTRE *(Thomson radiation) and LUX (undulator radiation) will soon come online and a second arm, delivering ps pulses, will be added to PFS-pro.*
CLF (GB)	The Central Laser Facility (CLF) provides a very broad spectrum of laser facilities, from high-intensity laser systems to ultra-fast sources and high-repetition-rate XUV beamlines, as well as a **complete suite of laser-based imaging and spectroscopy techniques.** GEMINI is a high-power ultra-short pulse CPA Ti:sapphire laser system delivering dual 0.5 PW / 30 fs [1/20 Hz] beams in the TA3 target area or a single 25 TW / 20 fs [1 Hz] beam in TA2 for investigation of secondary source generation and applications. *A new facility – EPAC (Extreme Photonics Applications Centre) – is being built at the CLF to replace GEMINI; it will comprise initially a 1 PW / 30 fs [10 Hz] laser housed, with two dedicated experimental areas, in a stand-alone building.* VULCAN is a PW-class Nd:glass laser system used for high-energy-density physics research and serving – with shots every 20 minutes – two target areas: TAW combines dual short laser pulses (2 x 100 TW / 1 ps) with six long pulses (6 x 80-280 J / 0.2-6 ns) while TAP is providing up to a 1 PW / 0.5 ps laser pulse coupled to one of these long beamlines. *The Vulcan 20-20 upgrade will increase the peak power of the Vulcan laser by 20 times, taking it from 1 to 20 PW; it will be achieved by upgrading six of the existing long pulse beams from <1.8 kJ to ~10 kJ and coupling them to one of the existing 100 TW beams, to the VOPPEL PW beamline (30 J / 30 fs @ 880 nm) and to a new very-high-intensity beamline (20 PW / 20 fs).* **Vulcan 20-20 will thus deliver the highest laser power on compressed targets.** ULTRA is a time-resolved (pump-probe) spectroscopy facility, which permits a range of ultrafast transient electronic and vibrational spectroscopic methods (2D, linear and nonlinear IR spectroscopy, TRMPS, FSRS, TAS, 2D-visible SFG, Kerr-gated fluorescence and Raman spectroscopy, and time-resolved resonance Raman spectroscopy) thanks to its multiple colour, pulse length and repetition rate laser systems serving OPA beamlines. ULTRA A and ULTRA B are CPA Ti:sapphire laser systems delivering respectively 4 mJ / 120 fs [1 kHz] + 1 mJ / 40 fs [10 kHz] + 1 mJ / 2 ps [10 kHz] and 2 mJ / 40 fs [10 kHz] laser pulses, while LIFEtime is a Yb:doped high-repetition-rate [100kHz] laser system delivering 0.07 mJ / 200 fs + 0.15 mJ / 300 fs. ARTEMIS is an ultrafast XUV science facility using 1 kHz and **100 kHz** (170 µJ [1.7 µm] + 50 µJ [3 µm]) ultrafast laser sources and **XUV beamlines** (harmonics) to study atomic and molecular physics, condensed matter physics and for coherent imaging. Endstations for ultrafast dynamics of condensed matter systems (time-resolved ARPES & spin-TOF) or in molecules (VMI & electron-TOF) are available to users. The OCTOPUS imaging cluster offers a suite of advanced laser-based imaging and laser trapping capabilities, such as multi-dimensional single molecule imaging and tracking, light sheet microscopy (LSFM), super-resolution microscopy (STORM, PALM, SIM, STED), cryo-microscopy or confocal microscopy (FLIM, FRET). *HiLUX (High average power Lasers for Ultrafast science aCROSS the spectrum) will increase the average power and repetition rate of the ULTRA and ARTEMIS lasers, providing a boost in instrument sensitivity and spectral coverage; the upgrade will include a new 100 kHz >200 W / sub-50 fs laser source @ 1 µm and additional endstations (e.g. time-resolved MOKE & XUV ptychography).*

ELI ALPS (HU)	The Extreme Light Infrastructure Attosecond Light Pulse Source (ELI ALPS) has the mission to provide **light sources of the shortest possible laser pulses (few cycles), in the broadest possible spectral regime (XUV – THz), at the highest possible repetition rate (10Hz-100kHz)**, for strong-field laser-matter interaction and temporal investigation at the attosecond scale of electron dynamics in atoms, molecules, plasmas and solids. - The Yb-fibre High Repetition (HR) laser system provides, at 1030 nm, 1.8 mJ / 30 fs [100 kHz] laser pulses, post-compressed down to 1 mJ / 6.5 fs (*↗ 5 mJ / <6 fs with CEP stabilisation*) to drive secondary harmonics (gas and condensed targets) sources serving TAS, ReMi (COLTRIMS), NanoESCA (LEED, XPS, PEEM, AES, RGA, momentum microscopy, ARPES, 2D spin analyser) and VMI endstations. A dedicated chamber for sample preparation is available to users. *An auxiliary (alignment) laser source (1 mJ / 7 fs [1 kHz]) will soon be operational.* - The OPCPA Mid-Infrared laser system (MIR) delivers 100 kHz 130 µJ / 42 fs pulses centered at 3.15 µm, post-compressed down to 70 µJ / <20 fs. A secondary harmonics (solid) source is available to users as well as VMI and ReMi (COLTRIMS) endstations. *MIR-HE will upgrade the performances of the primary source to >20 mJ / <50 fs, post-compressed to 10 mJ / <25 fs, delivered at 1 kHz in the 2600-3600 nm wavelength range or >12 mJ / <100 fs in the 1400-1700 nm range.* - The single-cycle NOPA laser SYLOS produces post-compressed 3.4 TW ↗ *15 TW* / <8 fs pulses around 891 nm and is complemented by the so-called SYLOS Experimental Alignment (SEA: 10 mJ ↗ 15 mJ / <4.5 fs), operated at a lower repetition rate [10 Hz]. SYLOS is used to generate secondary sources - harmonics *(gas & solid), electrons, ions & neutrons - and serve gas phase reaction control (GPRC), VMI and soon ReMi (COLTRIMS)* endstations. - The hybrid (Ti:sapphire-OPCPA) High-Field laser system (HF) consists of two laser systems fed by a common front end: HF-PW (>400 TW ↗ *2 PW* / 22-27 fs ↘ 17 fs [10 Hz]) *and HF-100 (50 TW / 10 fs [100 Hz]). HF will mainly be used to drive secondary harmonics (solid) and electron sources.* - The Nonlinear Terahertz Spectroscopy Facility (NLTSF) consists of 6 mJ / 220 fs [1 kHz] + 1TW / 500fs [50 Hz] Yb:CaF2 pump lasers at 1030 nm and of a THz / optical pump - THz probe system (coupled to optical spectroscopy and electro-optic THz detection setups); THz pulses with more than 200 kV/cm peak electric field are available on sample. *The High-Energy Terahertz Beamline (HE-THz) will reach more than 1mJ of THz energy.*
ELI Beam- lines (CZ)	The Extreme Light Infrastructure Beamlines (ELI Beamlines) will offer users **ultra-high-power (up to 10 PW) laser pulses with high repetition rates** –reaching ultra-high focused intensities up to 1024 W/cm2 – and a variety of sources of secondary radiation and particle beams that enable research in a broad range of applications in molecular, biomedical and materials science, as well as in fundamental studies of laser-plasma interaction and high-energy-density physics for which the combination of PW and kJ laser beams on target is a key feature. The L1 ALLEGRA OPCPA laser system delivers 3.6 TW ↗ *6.5 TW* / 15 fs / 750-920 nm pulses at <1 kHz *(soon to be synchronised to a second >10 mJ beam)*. It drives secondary harmonics (gas) and plasma x-ray (PXS) sources for multidisciplinary physics experiments using four endstations: MAC (electron- and ion-ToF, VMI, MBES, CDI), TREX (XRD, XRS, XAS, XES and pulse radiolysis), optical spectroscopy (FSRS, TAS, TCT & 2D IRS) and trELIps. The *ALFA kHz secondary electron source will also be soon available in E1.* *The L2 Dual-beam Ultra-fast High energy OPCPA Amplifier (DUHA) is designed to provide 120 TW / 25 fs pulses at 820 nm and at >20 Hz high repetition rate, passively synchronised to a 5 mJ / 30 fs / 2.2 µm [2 kHz] auxiliary output. The main role of DUHA is to drive laser-driven wakefield acceleration, where higher average power is desired and PW-level intensities aren't necessarily required, and induced XFEL-like radiation (LUIS beamline).* The L3 High-Repetition-Rate Advanced Petawatt Ti:sapphire Laser System (HAPLS) is generating 500 TW ↗ 1 PW / <28 fs pulses at 800 nm at a repetition rate of <3 1/2 Hz ↗ 10 Hz for plasma physics experiments and to drive electron, x-ray *(Compton and betatron) and ion secondary sources. The ELBA electron beamline will achieve the highest energy and high quality electron beams, while the ELIMAIA ion beamline will be used, amongst other applications, for medical applications (thanks to the ELIMED beam transport and dosimetry line).* The L4 ATON OPCPA laser system can operate in two regimes: 1/ a long kJ-class laser beam – 600 J ↗ *1.2 kJ* / 2, 3 and 10 ns ↗ 0.5-10 ns @ 1.053µm [1 shot/2 min ↗ *1 shot/min] - coupled to a short PW-class beam – 1 PW / 150 fs / 1.060 µm beam [1 shot/min] - or 2/ one single extremely high peak 10 PW / 150 fs / 1.060 µm beam [1 shot/min] for laser-matter interaction research or particle acceleration.*

ELI-NP (RO)	The Extreme Light Infrastructure Nuclear Physics (ELI-NP) Ti:sapphire High Power Laser System (HPLS) has a dual-arm architecture fed by a common front-end. Experimental areas have been implemented at various laser energy levels allowing experiments at 820 nm with 2 x 100 TW / *22 fs [10 Hz], 2 x 1 PW / 25 fs [1 Hz] or 2 x 10 PW / 23 fs [1 shot/min].* ELI-NP will be the ***most advanced RI in the field of photonuclear physics once the PW beams, and its secondary particle (neutron & positron) and radiation sources are coupled to a g-ray beam*** *(with tunable photon energy up to 19.5 MeV and spectral density above 1000 ph/s/eV).* ELI-NP successfully finalised the commissioning of its High-Power Laser System, currently the most powerful laser in the world, delivering 2x 10 PW at 1 shot per minute, 2 x 1 PW at 1 Hz and the 2 x 100 TW at 10 Hz pulses and the first commissioning experiments are being implemented.
LULI (FR)	As a national infrastructure dedicated to laser-matter interaction and its applications, the Laboratoire pour l'Utilisation des Lasers Intenses (LULI) is operating multi-beam laser facilities providing opportunities to couple high-energy light pulses to high-power ones and to external pulsed high-amplitude magnetic fields. The APOLLON CPA Ti:sapphire RI is dedicated to secondary particle and radiation source generation and applications, and to high field physics, thanks to, currently, 1 PW / 20 fs laser beam (F2 – 1 shot per minute) and two experimental areas (one using long focal length focusing optics - LFA - dedicated to electron acceleration, and one using short focal length focusing optics - SFA - dedicated to ion acceleration and QED physics). Three beams will be progressively added – F1 (4 ↗ 10 PW / 20 ↘ 15 fs), F4 (100 mJ / 20 fs) and F3 *(delivering the remaining energy, up to a total of 250 J, in the ns regime) – to complete the foreseen* ***multi-beam multi-PW RI.*** LULI2000 is a Nd:glass laser platform dedicated to high-energy-density physics thanks to two high-energy 800 J / 1.5-15 ns beams (one of them possibly compressed down to 100 J / 1 ps), one auxiliary probe beam 50 J / 1.5-15 ns, and two experimental rooms; 1 shot at full energy is delivered every 90 minutes. An electromagnetic pulser can be implemented close to the target chambers to allow production of external magnetic fields of ~40 T. HERA is dedicated to laser shock generation and material study (LIDT, shock peening and adhesion and mechanical testing); the Nd:glass laser system delivers, every 20 minutes, 200 J / 5-15 ns pulses. *A second beam, with the same parameters, will soon be operational.*

Large-scale RIs

CETAL (RO)	Due to the high technological level of its equipment, the Center for Advanced Laser Technologies (CETAL) is a very important facility in Romania in the field of high-power laser-based technologies for academic and industrial applications, making it a **valuable support to ELI-NP** it contributed to promote. The Laboratory for laser interactions in ultra-intense regime (CETAL-PW) aims to explore laser-matter interaction at ultra-high intensities, focusing on applications – mainly through radiation and particle secondary sources – through two CPA Ti:sapphire laser systems: CETAL-PW (1 PW / 25 fs [0.1 Hz]) and TEWALAS (15 TW / 25 fs [10 Hz]). Ultrashort laser-induced damage testing of optical components is also addressed. The Laser materials processing laboratory (CETAL-LaMP) focuses on laser processing of various materials (polymers, glasses, ceramics, metals, composites) at macro-, micro- or nanometre scale. Workstations for 3D lithography, 3D additive manufacturing, 3D printing, PLD, cutting-welding-cladding and surface structuring are made available to users. The Laboratory for photonic investigations (CETAL-PhIL) allows spectroscopic investigations – by THz and Raman spectroscopy, LIBS, AAS and spectrofluorimetry – as well as vibrometry and spectroradiometry tests. In addition, the facility supports ultrafast laser fabrication of 3D microfluidic devices for biomedical applications. *A new generation for the pump lasers of the PW amplifiers will increase the availability of the primary and secondary sources, while new fibre-based fs laser sources will extend the imaging and spectroscopic capabilities. Upgrades of the existing instruments are also planned (for instance the 3D lithography equipment, towards faster processing and higher throughput, or the microfluidic facility, to accommodate a time-lapse confocal high-resolution fluorescence microscopy setup).*

CLPU (ES)	The Centro de Láseres Pusados (CLPU) is the key Spanish RI that specialises in high-intensity ultrashort lasers. The architecture of the Ti:sapphire laser system VEGA offers users access to three independent and synchronised beamlines: VEGA-1 (20 TW / 30 fs [10 Hz]), VEGA-2 (200 TW / 30 fs [10 Hz]) and VEGA-3 (1 PW / 30 fs [1 Hz]), as well as to VEGA-2 laser-driven electron, proton and betatron radiation secondary sources. The high repetition rate at the PW level of the VEGA facility, as well as the **innovative high-repetition rate gas and liquid targetry** available, makes it a valuable support to ELI-Beamlines. In addition to the VEGA facility, CLPU operates the ULAMP laboratory that provides a high-quality service focused on laser machining (laser shock peening, laser drilling-cutting-welding, LIDT) as well as a microscopy unit (SEM, EDX, EBS, optical microscopy). *Additional low-peak-power laser systems (including a kHz few-cycle µJ and a 10 Hz J-level ns sources) will soon be added to the VEGA facility for pump-probe experiments, and synchronisation at the shortest possible level of all the beams will also be achieved. Finally, a new target area will be commissioned to foster multiple parallel activities.*
GSI/PHELIX (DE)	The GSI Helmholtz Zentrum für Schwerionenforschung (GSI), hosting both the PHELIX laser facility and ion accelerators, offers the **unique opportunity to combine, on target, MeV heavy ion and high-energy laser beams.** PHELIX is a versatile single-beam Nd:glass laser facility delivering <280 TW / 0.5 ps pulses every 90 minutes. One low-power (<10 TW) target area and one full-power stand-alone target area are available to users for laser-plasma interaction experiments and for the generation and applications of secondary sources. A programmable nanosecond front-end allows for <1 kJ pulses with a deterministic pulse profile within a 0.5-10 ns window at the PW target area and, as the PHELIX beam can be split in two sub-beams, the combination of long and short pulses (with a delay above 200 ps) is made possible, but at limited energy (<30 J each). A third target area (Z6) allows for combined laser / UNILAC <13 MeV ion beam experiments; PHELIX is then coupled to the nhelix beamline (100 J in the ns regime or 20 TW / 500 ps) for laser-based diagnostics. PHELIX is also driving a laser-accelerated proton beamline (LIGHT). *A new target area (HHT) dedicated to combined laser / SIS-18 <1 GeV ion beam experiments will soon be open to users.*
HZDR/ELBE (DE)	ELBE at the Helmholtz Zentrum Dresden-Rossendorf (HZDR) consists in two high-power laser systems, in addition to a superconducting electron accelerator and its secondary radiation sources. The first CPA Ti:sapphire laser system, DRACO is delivering, at 1 Hz, two laser pulses (670 TW and 150 TW / 30 fs) to be used separately or in combination with the ELBE-generated radiation sources. Brilliant secondary laser-driven radiation and particle sources are produced and used for, for instance, radiobiology applications. As an example, a dedicated beamline to transport the DRACO-accelerated ion beams is available for **high dose rate irradiation of biological samples.** *The second laser system is still under development. PENELOPE, a diode pumped Yb:CaF2 1 PW / 150 fs / 940 nm [1 Hz] laser system, represents the next generation of high-power lasers. It will soon come online, first for ion acceleration applications within the Helmholtz ATHENA project. This project will also allow commissioning of a target area fully dedicated to radiobiology applications and basic research. Extended multi-beam capability at the PW level will also be implemented.*
PALS (CZ)	The Prague Asterix Laser System (PALS) facility operates a kJ-class photodissociation iodine laser system **(the only iodine RI in Europe)** at a wavelength of 1315 nm and a pulse duration of 350 ps for laser-matter interaction at high energy density as well as for electromagnetic radiation generation and mitigation. The laser system delivers, every 25 minutes, two beams, the main one at 600 J and an auxiliary one at 100 J. Both beams are precisely synchronised with a CPA Ti:sapphire laser beam (22 TW / 45 fs [10 Hz]) used mainly as a probe beam. *An upgrade of one of the key plasma diagnostics – a multiframe fs interferometry instrument – and new particle diagnostics are planned.*

Mid-scale RIs

CELIA (FR)	CELIA (Centre Lasers Intenses et Applications) proposes three reliable lasers systems, including a **unique MHz Yb:fibre laser source**, secondary (harmonics, X-Ka, betatron) radiation sources, and nine fully equipped endstations (XANES, attosecond metrology, VMI, COLTRIMS, FDI, polarimetry, shadowgraphy, Raman spectroscopy) dedicated to a number of specific applications. AURORE (Ti:sapphire: 2x7 mJ / 25 fs, post-compressed down to 2 mJ / 7 fs [1 kHz]) ECLIPSE (Ti:sapphire: 5 TW / 30 fs (post-compressed down to 10 mJ / 10 fs) [10 Hz] or 2x30 TW / 30 fs [1 Hz]) BLASTBEAT (Yb:fibre: 2 x 50 W / 130 fs / 1030 nm [0.166-2 MHz]) A radioprotected experimental area is open on ECLIPSE for ultra-high-intensity laser-matter interaction experiments. A GHz Yb-based laser micromachining bench is also available. *The upgrade of AURORE is ongoing for improved stability and mode quality. A sub-10 fs VUV-DUV beamline is under development on BLASTBEAT and a new time-resolved ARPES endstation will be funded.*
CNR/ILIL (IT)	The Intense Laser Irradiation Laboratory (ILIL) operates a CPA Ti:sapphire chain delivering two laser beams (10 TW/40 fs [10 Hz] and& 240 TW/25 fs [5 Hz], possibly frequency doubled) into two independent multi-purpose target chambers equipped with long and short focal length off-axis parabolas focusing laser pulses on solid and gas targets with micrometer accuracy positioning. The lab provides in addition direct access to very-high-energy electron and light ion beamlines at very high dose rates, for sample irradiations and pre-clinical studies. A kHz Ti:sapphire laser system (20 mJ/30 fs) is also accessible, directly, or to pump a two-stage OPA to generate mid-IR pulses from 1.3 µm to 2.9 µm. *It is foreseen that an additional J-level (30 fs [100Hz]) will be added to the facility for high-average-power high-throughput applications. ILIL is part of the National Institute of Optics of the National Research Council of Italy.*
ENEA/ABC (IT)	The ABC facility, operated at the ENEA Frascati Research Centre, comprises **two-counter-propagating-beam Nd:glass laser system** (2 x 100 J / 2.5-7 ns [1 shot per 30 minutes]), complete with a 4-beam probe laser system (4 x 100 mJ / 0.5 ns / 0.53 µm), and a well-equipped experimental area for fusion-related, EMP and multi-purpose (e.g. testing of advanced materials, aerospace or biology) studies.
HIJ (DE)	The Few-Cycle-Laser laboratory at the Helmholtz Institute Jena (HIJ) operates various laser sources for the investigation of strong field and attosecond laser physics, as well as for the generation and use of secondary particle and radiation sources. POLARIS is an **all-diode pumped laser system currently reaching the highest peak power worldwide** for such a system (200 TW / 100 fs / 1030 nm [1/50 Hz]), while JETI200 is a Ti:sapphire laser system delivering 200 TW / 20 fs / 800 nm [5 Hz]; additional kHz mJ-class few-cycle laser sources are also available and on-**shot CEP phase metrology** is operational. Apart from laser-matter diagnostics, techniques such as momentum (COLTRIMS) and photoelectron microscopies are present in the lab. *A new target area for combined POLARIS – JETI200 experiments will be commissioned and focal lengths up to 10 m implemented.*
HiLASE (CZ)	HiLASE provides a **unique platform for industrial partners** by operating two diode-pumped solid-state (Yb:YAG) kW laser facilities. BIVOJ delivers 100 J / 10 ns / 10 Hz laser pulses, while PERLA generates 13 mJ / <1.5 ps / 1 kHz pulses at the fundamental wavelength (PERLA B) or, at lower energy but higher repetition rate (50 or 100 kHz), over a broad spectral region from 200nm to 3.5µm, thanks to harmonic generation and OPA (PERLA C). Dedicated stations for laser shock peening, LIDT or laser micro-machining are available, as well as state-of-the-art characterisation devices (SEM, XRD, AFM, LCSM and Raman spectroscopy). *A new versatile laser beam delivery system to experimental areas will soon enable switching and combination of beams. The PERLA will also be upgraded to the Joule level at 500 Hz. In the longer term, four new national strategic programmes should support additional services and upgrades (towards increased average power and repetition rate, shorter duration, and wider wavelength coverage).*

LIDYL (FR)	LIDYL (Laboratoire Interactions, Dynamiques et Lasers) combines a series of complementary ultrafast lasers and advanced experimental workstations to study a large variety of ultrafast phenomena in gas, solids and plasma: UHI100 (Ti:sapphire – 100 TW or 2 x 50 TW / 25 fs /10 Hz) for studying laser-plasma interaction at ultra-high intensity / very high temporal contrast, laser acceleration and applications of secondary particle beams; ATTOLab, associating the Ti-sapphire, CEP stabilised FAB1-10 laser (15 mJ / 25 fs / 1 kHz or 2 mJ / 25 fs / 10 kHz) with two harmonic beamlines providing **VUV-XUV fs/as pulses** (up to 100 nJ @ 1 kHz or 10 nJ a@ 10 kHz) **with adjustable spectral bandwidths and OAM**, for ultrafast studies in the gas (COLTRIMS, VMI and MBES) and solid phases (ARPES, TOF-SPIN); NANOLIGHT (post-compressed Yb OPCPA –300 µJ / 50 fs @ 1 µm, 15 µJ / 38 fs @ 1.8 µm, 13 µJ/ 65 fs @2.4 µm [100 kHz]); XUV harmonic beamlines (up to 60 eV from gases or up to 26 eV from crystals) are also available; FLUME, a **rare FLUPS set-up in the visible and UV regions (down to 267 nm) with 100 fs resolution** to study time-resolved emission spectra of molecules in the condensed phase. *An upgrade of the ATTOLAB facility (to reach the 100 kHz repetition rate) is foreseen.*
LOA (FR)	LOA (Laboratoire d'Optique Appliquée) provides unique instrumentation in the field of ultrafast laser-plasmas with laser duration down to an optical cycle and **high repetition-rate, multi-beams synchronised at the fs timescale**, and fixed experimental setups: Jaune (Ti-sapphire: 10 Hz / 2 x 60 TW / 30 fs coupled to 0.5 J / 500 ps and, possibly, six low-energy laser beams) serving four beamlines for studies of electron acceleration (and related applications, such as x-ray induced – Compton, betatron – sources) and XRL (1 µJ / 300 fs / 30 nm) Noir (post-compressed Ti:sapphire: 1 TW / 3.5 fs / 1 kHz) for electron / proton acceleration and XUV harmonic emission from solids Violette (Ti:sapphire : 15 mJ / 50 fs [100 Hz]) for lasing in gas, THz and acoustic generation and (Ti:sapphire: 6 TW / 50 fs [10 Hz]) for filamentation and laser-induced breakdown Corail/Argent (Ti:sapphire OPCPA: 3 mJ / 40 fs / 5 kHz coupled to <1 mJ / 30 fs / 1 kHz) serving five beamlines for ultra-fast solid-state physics, THz time-domain spectroscopy and femto-magnetism studies, as well as soft x-ray imaging and metrology. *A new laser source (1 J / 25 fs / 100 Hz) will be commissioned in the future. The related LAPLACE project, which also involves the construction of a* ***new beamline devoted to high-dose radiobiology using electrons and X-rays****, will reinforce the Greater Paris leadership in laser-plasma acceleration.*
LNF/SPARC_ LAB (IT)	The SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Laser And Beam) facility at the National Laboratory of Frascati (LNF) consists of a conventional high-brightness RF photo-injector SPARC (delivering up to 170 MeV electron bunches and a tunable and high intense THz source) and a CPA Ti:sapphire laser FLAME (200 TW / 25 fs plus <2 TW / 30 fs [10 Hz ↗ 100 Hz]). FLAME is employed to study laser-matter interaction, including LWFA electron acceleration and betatron radiation or TNSA ion generation. An external injection beamline allows the study of **acceleration of an electron bunch by a laser-driven plasma wave.** *In the framework of the EuPRAXIA@SPARC-LAB project, it is planned to build a 1 GeV X-band RF linac and to upgrade FLAME up to the 0.5 PW range.*
STRATH/SCA- PA (GB)	The Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) at the University of Strathclyde hosts three CPA Ti:sapphire laser systems (350 TW / 25 fs [5 Hz] – 13 mJ / 25 fs [1 kHz] – 40 TW ↗ 100 TW / 35 fs [10 Hz]) and the ALPHA-X (Advanced Laser Plasma High-Energy Accelerators towards X-rays) beamline. *A new beamline dedicated to plasma photonics will be commissioned in the near future.* It is home to the Plasma Accelerators for Nuclear Applications and Materials Analysis (PANAMA) facility which aims to provide state-of-the-art characterisation and **testing capabilities for nuclear materials** thanks to the SCAPA primary and secondary sources. *Capabilities include XCT as well as, soon, XAS and XRD.*

Small-scale RIs and stations

CALT (HR)	The Centre for Advanced Laser Techniques (CALT) aims to lead laser-based research in Croatia and the wider region. It is committed to scientific excellence in femtochemistry, quantum technology, material science and plasma research. Currently, two laser systems are installed: a Nd:YAG one (100-850 mJ / 5 ns / frequency convertible up to the 4th harmonic [1-20 Hz]) for laser processing and a Ti:sapphire one (7 mJ / <100 fs / 290 - 2600 nm [1 kHz]) for ultrafast dynamics and optical microscopy research. *Once completed, CALT will operate a series of laser systems, cw or at high repetition rate (from 1 to 200 kHz), covering a large range of wavelengths, as well as an ultra-stable optical (450-2000 nm) frequency comb synthesiser and a magneto-optical trap for Ru atoms. A variety of spectroscopy / microscopy / imaging techniques will be available, amongst which the most innovative are time-resolved ARPES, nano-FTIR, SNOM, CRDS, LIBS and ICP-OES.*
CLL (PT)	The Coimbra Laser Lab (CLL) specialises in photochemical, photophysical and spectroscopic studies, from the IR through the UV, covering timescales from fs at room temperatures to ultra-slow processes at cryogenic temperatures. It focuses notably on biomedical applications (e.g. photodynamic therapy) or energy (organic polymeric and inorganic photovoltaics, LEDs, etc). It operates a series of cw and pulsed lasers or LEDs, plus cryogenic systems and a cell lab, serving a large variety of techniques: fs-ns NIR-UV TAS, TCSPC, FLUPS, time-resolved photoacoustic calorimetry and tomography, Raman spectroscopy, IR and Raman mapping, **chirped-pulse Fourier transform microwave spectroscpy** or FLIM. *A super-resolution (100 nm) fluorescence imaging and a high-repetition-rate mJ laser source will be soon commissioned.*
CLUR (ES)	The Ultrafast Lasers Center (CLUR) at the Universidad Complutense de Madrid specialises in the application of pulsed lasers to process materials, as well as in the synthesis of nanostructured materials and femtochemistry. It operates a series of ns / <1 J / 202-1064 nm [10 Hz] laser systems, as well as the Ti:sapphire FEMTO1 (3.5 mJ / 35 fs / OPA 235 nm – 3 µm) and FEMTO2 (1 mJ / 80 fs) kHz laser systems, which – combined with molecular beam apparatus – allow charged particle imaging techniques (REMPI, electron and ion TOF, VMI, slice imaging), FLUPS and laser processing. *A new Ti:sapphire laser source (3.6 mJ / 1 kHz / 5 fs) serving a XUV attosecond beamline is under construction.*
CUSBO (IT)	Several unique state-of-the-art sources at CUSBO (Center for Ultrafast Science and Biomedical Optics) provide few-cycle light pulses, either widely-tunable or of high peak power: - STRATUS (Ti:sapphire OPA: 100 fs / 1 mJ @ 800 nm / 500-2000 nm [1 kHz]) - post-compressed Ti:sapphire SERAPIDE (1 mJ / 4 fs [10 kHz]), ELYCHE (2.5 mJ / 4 fs [1 kHz]) and FEXRAYS (0.8 mJ / 5 fs [1 kHz]) - ULTRAS-TW (Ti:sapphire OPA : 1.5 mJ / 20 fs / 1200-1900 nm [10 Hz]) These sources are used to seed isolated attosecond and XUV (14-55 eV / 15 fs) harmonic beamlines for pump-probe experiments. Additional tunable visible (430-480 and 500-700 nm) and near-IR (900-1500 nm) NOPA sub-30 fs laser sources are also available. Workstations based on **highly time-resolved** techniques (especially **2D electronic spectroscopy techniques from the near-IR to the UV**) allow for, for instance, non-invasive clinical diagnostics and in-vivo monitoring, non-destructive analysis of food and cultural heritage; techniques include spectrally-resolved photoluminescence, ARPES, LSFM, SIM and Raman spectroscopy. *New workstations should soon be commissioned, and new techniques implemented, amongst which are: multifunctional time-domain diffuse optical tomography, multiscale high-resolution, or the use of quantum light for ultrafast spectroscopy and imaging.*
DESY/CFEL-ATTO (DE)	The Femtosecond and Attosecond Laser Spectroscopy group at the Center for Free-Electron Laser Science (CFEL-ATTO), located on DESY's Hamburg campus, offers access to the FLASH free electron laser, in addition to a series of beamlines: - XUV (15-50 eV) attosecond (200 as) nJ-level pulses combined with sub-2 fs UV (210-340 nm) and sub-4 fs NIR (450-1000 nm) pulses for **3-color ultra-fast covariance detection** (electron/ion VMI, ion mass spectrometer, molecular beams and liquid jet available), - an IR synthetiser driving an attosecond soft x-ray (280-530 eV) beamline, - two home-made laser systems for high-energy applications (1 J / 300 ps / 1.03 µm [300 Hz] and 100 mJ / 900 fs / 1.02 µm [1 kHz]), - a high-average-power IR frequency comb (80 W / 200 fs post-compressed to 40 fs /1.03 µm [65 MHz]) fully stabilised.

HEPHAESTUS (BG)	The Extreme Coherent Light in the Mid-IR and X-Ray Area as a Laboratory Infrastructure (HEPHAESTUS) is located within the John Atanasoff Center for bio- and nano-photonics. It provides access to a series of fs-class >kHz laser sources, covering a wide range of wavelengths (from 240 nm to 2.6 µm) at the sub-10 mJ energy level, to ns-class >Hz laser sources and to secondary harmonic sources. A variety of techniques and instruments are available: TAS instruments in UV, VIS, NIR and mid-IR spectral ranges, TDRS, AFM, FLUPS, TCSPC or LIBS, for biological and material science applications. *New laser sources will complement the offer, including a mid-IR tunable (2.45-9* µm) fs one for mid-IR TAS or table-top x-ray lasers, currently under construction.
ICFO (ES)	ICFO (Institut de Ciències Fotòniques) aims to advance laser science, focusing notably on **few-cycle CEP-stabilised laser sources at high repetition rate (>kHz) and high average power, with wavelengths ranging** from the UV **to the mid-IR**. The available sources include a Ti:sapphire ultra-broadband (1.1-2.4 µm) post-compressed OPCPA system (<2 mJ / <12 fs @ 1.8 µm [4 kHz]), a Nd:YV04 post-compressed OPCPA system (16 µJ / 15 fs / 3.2 µm [160 kHz]) and a Ho:YLF OPCPA system (0. 7mJ / 188 fs / 7 µm [100 Hz]). An **attosecond XUV / soft x-ray** (up to water window) **harmonic beamline** is available to users, as well as cutting-edge microscopy techniques (STED, STORM/PALM, Raman microscopy, LCSM, LSFM, FLIM, AOSLO, COLTRIMS, LIED), combined to allow multimodal imaging, and laser machining tools. *Upgrades of the attosecond soft x-ray beamline towards higher flux, and of the spectroscopy instruments towards higher resolution (1/3000 at the O edge), are planned.*
IEP-TU Graz/ NanoESCA (AT)	The Institut of Experimental Physics (IEP) at the Graz University of Technology operates the NanoESCA instrument for fs absorption microscopy and time- / energy- / momentum-resolved photoelectron microscopy (PEEM, ARPES). *The latter instrument will be soon upgraded to reach a few fs temporal resolution.*
IJCLAB/LASERIX (FR)	LASERIX at the Laboratoire de physique des deux infinis Irène Joliot-Curie (IJCLAB) is a 40 TW laser facility comprising three 40 fs / 10 Hz distinct beamlines (40 TW, 30 mJ and 1 mJ) dedicated to (i) applications of XUV harmonic and soft x-ray laser secondary sources, (ii) laser-plasma electron acceleration, and (iii) vacuum QED and strong-field physics. *A new compressor and a radio-protected experimental area, and the coupling of the laser to a photo-injector (PHIL), will allow new routes for light-matter and photon-electron interaction studies.*
IPPL-HMU (GR)	The ZEUS Ti:sapphire laser facility (45 TW / 23 fs [10 Hz]) at the Institute of Plasma Physics and Lasers (IPPL) of the Hellenic Mediterranean University (HMU) in Greece (not to be confused with the Zettawatt-Equivalent Ultrashort pulse laser System at the University of Michigan) allows access to secondary plasma-generated radiation (1-10 keV, tunable XUV ~30-100 nm and acoustic) and particle (50-100 MeV electrons, 1-2 MeV protons) sources. Auxiliary lasers (including a 7 fs / 2 mJ [1 kHz] CEP-stabilised Ti:sapphire source, 10 Hz Nd:YAG sources in the ns (up to 850 mJ) and ps regime (250 mJ) and fibre CW 2 kW at 1.08 µm) are also available for material science or laser fusion basic physics.
ILM/X-2M (FR)	X-2M at the Institut Lumière-Matière (ILM) of CNRS and University of Lyon provides several beamlines devoted to the study of atomic/molecular, solid or liquid targets using light pulses at extreme wavelengths, over a broad spectral domain, from THz to extreme UV. Intense femtosecond THz pulses (2-40 THz) and extreme UV (10-100 eV) pulses are delivered with durations from tens of femtoseconds to hundreds of attoseconds. These beamlines are driven by a post-compressed CEP-stabilised Ti:sapphire laser source (1 mJ / 7 fs [5 kHz]). Two tunable mid-IR (2-4 µm) laser sources (at 10 Hz and 300 kHz) are also available. Several endstations are accessible by users (2 VMI, 3D and linear ion trap mass-spectrometers, TOF and Triple Quad mass spectrometers, liquid chromatography and 2 IRMPD set-ups). *A new endstation devoted to soft x-ray TAS and fluorescence spectroscopy will be soon commissioned.*
IPHT/LPI (DE)	*The Leibniz Center for Photonics in Infection Research (LPI) will help to revolutionise the development of market-ready light-based diagnostic methods and novel therapeutic approaches for the treatment of infectious diseases from 2028. It will provide external users with access to spatially-resolved and time-resolved spectroscopic imaging technology stations, novel multimodal imaging technologies from the XUV to FIR spectral ranges, and photonic molecular biological point-of-care technologies. Photonic technologies will be combined with biomedical technologies, such as different "omics" methods, next-generation sequencing, and other enabling technologies such as microfluidics.*
ISMO (FR)	The Institut des Sciences Moléculaires d'Orsay (ISMO) performs theoretical and experimental research on systems ranging from atoms, plasmas, molecules, nano-objects and molecular films, living cells and tissues, based on access to a wide variety of facilities, including on-site nanosecond to femtosecond lasers. ISMO leads the development of advanced techniques made available to users, such as **super-resolution nanoscopy**, and operates stations dedicated to optical bio-microscopy, gas phase analysis (VMI), SFG or Raman spectroscopy. *Evolution towards the near IR is planned.*

IST/IPFN (PT)	At IST/IPFN (Instituto Superior Técnic/Instituto de Plasmas e Fusão Nuclear), two labs are operating national-scale laser facilities. L2I (Laboratory for Intense Lasers) is dedicated to the study of laser-matter interaction at very high optical powers thanks to two high-repetition-rate laser sources: L2I MIR (65 µJ ⇗ *1 mJ* / 40 fs / 3.2 µm [100 kHz]) and L2 NIR (1 mJ / 1 ps / 1.03 µm [100 kHz]). VOXEL (VOlumetric medical X-ray imaging at Extremely Low dose) hosts several lasers, including the most recent one, an ultra-short and ultra-intense infrared light source (Ti:sapphire – 5 mJ / 35 fs [1 kHz] or 25 mJ / 40 fs [10 Hz]). *Post-compression will be soon implemented to reach sub-fs duration.*
LACUS (CH)	The Lausanne Centre for Ultrafast Science (LACUS) offers various instruments for the investigation of matter (for solar and electronic applications, complex quantum materials, nano-structures, molecular systems) in out-of-equilibrium conditions. It offers access to three facilities: - HARMONIUM, a high-order harmonic source (served by a 15 W [6 kHz] NIR source) providing VUV (15-100 eV) fs pulses to a beamline for steady-state and time-resolved ARPES, complemented by the YPERION XUV source (9-11 eV [1 MHz]) - LOUVRE, a 20 kHz laser source for UED and visible and UV TAS - LUMES, fully renewed, which offers ultrafast TEM and EELS setups with fs-Å-eV resolution
Laserlab DK (DK)	Laserlab DK is an interdisciplinary Danish network aimed at strengthening the development of advanced laser light sources for applications within both industry and research; it offers a frequency metrology facility (based on fs frequency combs) as well as user facilities for experiments with fs pulses ranging from the THz regime to VUV.
Laserlab-NSC (FI)	The Laser Laboratory of the Nanoscience Center (Laserlab-NSC) combines laser spectroscopy with nanoscience thanks to three fs laser systems and, with more than ten other spectroscopic setups, enables various experiments in time- and frequency domains and also imaging. Laserlab-NSC focuses on vibrational spectroscopy (IR and Raman), nonlinear spectroscopy and imaging, biomolecular spectroscopy, plasmonics, and the development of analytical methods. *Access to an SNOM facility is available.*
Laserlab-Sweden (SE)	Laserlab-Sweden is a network of Swedish laser RIs, established to promote and stimulate the efficient use of existing laser infrastructures at Swedish universities. It serves a cross-disciplinary user community, from academia, to research institutes, to medical centres, as well as industry.
LENS (IT)	LENS, the European Laboratory for Non-Linear Spectroscopy, is a centre of excellence at the University of Florence. Research interests include photonics, biophysics, chemistry and atomic physics. Several facilities are proposed for THz spectroscopy, ultrafast force-clamp spectroscopy, light-sheet microscopy, SNOM, TAS, single molecule tracking microscopy, super-resolution imaging and optical Kerr spectroscopy, as well as for direct laser writing and investigation of ultracold quantum matter. *New services (for studying materials under ambient conditions and for time-frequency measurements) are foreseen.*
LLAMS (NL)	The mission of the Institute for Lasers, Life and Biophotonics (LaserLaB) Amsterdam is to perform research, using the interaction of (laser) light and matter, on systems ranging from atoms and molecules to living cells and tissues. Apart from molecular physics and ultra-precise spectroscopy, there is a strong focus on the further development of new methods, techniques and tools to study fundamental aspects of living systems. LLAMS operates a series of laser sources, including a tunable pulsed dye laser source and the TeraWatt facility (Ti:sapphire NOPA – 2 x 2.5 mJ / 7.6 fs / 720-1040 nm [30 Hz]), as well as secondary harmonic sources and complementary setups (frequency combs, multi-trap optical tweezers). Multiple endstations and techniques are available (TAS, LSFM, OCT, SRS, SHIM, STED, IRS or single molecule tracking microscopy), some of them being unique within the Laserlab-Europe consortium (**NICE-OHMS**, **crossed molecular beam VUV-laser facility**, near-IR - watermarked stimulated Raman spectroscopy, IR diffusion-ordered spectroscopy, dark-field scattering microscopy and spectroscopy). *An upgrade of the SRS microscopy is planned to operate in the visible as well as the near-IR range.*
LLC (SE)	The laser sources operated by the Lund Laser Center (LLC) include, amongst others, two CEP-stabilised laser sources - Attolab (Ti:sapphire OPA – 5 mJ / 20 fs / 770-830 nm [3 kHz]) and, especially, a **200 kHz few-cycle Yb:rod NOPA** (MHz: 15 µJ / 6 fs / 850 nm) – and a terawatt Ti:sapphire dual-beam facility (40 TW / 35 fs [10 Hz]). Several laboratories are available for users, for quantum optics (using cw single-mode laser source and cryostats), femtochemistry (with, for exmple, a sub-ps THz spectroscopy set-up), combustion (which allows diagnosing matter in **harsh environment**) or biomedicine (fluorescence diagnostics). Additionally, CARS, LIDAR and fs LIF setups are available. *The terawatt laser source will be very soon replaced by a dual 50 mJ / [100 Hz] + 250 mJ [10 Hz] / <10 fs OPCPA T^3 laser and a short-wave IR OPCPA system (13 µJ / 15 fs / 1.8 µm [200 kHz]) will be made available.*

LP3 (FR)	ASUR is the major laser source operated at the laboratoire Lasers, Plasmas et Procédés Photoniques (LP3: Ti:sapphire – 20 TW / 25 fs [10 Hz] or 10 TW / 25 fs [100 Hz]); it allows driving a pulsed **hard (17.5 and 8.05 keV) x-ray source at** a repetition rate of **100 Hz** for x-ray imaging and diffraction. The services available at LP3 focus on laser damage down to the ultrashort (15 fs) regime, **innovative laser micro-processing for matter functionalisation and transformation** (including additive fabrication and printing by LIFT, nanoparticle fabrication, structuration of, notably, dielectric and semi-conductor materials, using Gaussian or Bessel beams) and elemental analysis through LIBS. *Additional setups (time-resolved XRD, LIFT-based bio-printing and time-resolved polariscopy) will be commissioned in the near future.*
MBI (DE)	The Max-Born-Institut (MBI) conducts basic research in non-linear optics, ultrafast dynamics and laser-matter interaction, and into the resulting applications, thanks to a series of ultrashort and ultrafast lasers over a wide laser spectral range, from 800 nm to 5 µm: - a Ti-sapphire OPCPA laser source (190 µJ / 7 fs [100 kHz]), - a post-compressed Yb:YAG OPA laser source (>3 TW / 9 fs / 1030 nm [100 Hz]), - a **IR / mid-IR dual-beam 100 kHz Yb:YAG OPCPA system** (430 µJ / 51 fs / 1.55 µm + 125 µJ / 73 fs / 3.1 µm), - a multi-MW Ho:YLF OPCPA laser source (3.1 mJ / 80 fs / 5 µm [1 kHz]). These laser sources serve a variety of >kHz secondary (harmonic and Kα) radiation sources for, notably, **all-attosecond pump-probe spectroscopy** setups using various techniques (VMI, MBES, TAS, COLTRIMS, electron and ion TOF, THZ spectroscopy, optical Kerr spectroscopy) and **combination of different probing wavelengths** (THZ/UV – VUV/soft x-ray).
MPQ (DE)	Research being undertaken at the Laboratory for Attosecond Physics of the Max-Planck-Institute for Quantum Optics (MPQ) is aimed at developing basic tools for the real-time observation of, and control over, electronic motion on an atomic scale; the group relies mainly upon CEP-stabilised ultra-short laser sources serving attosecond XUV beamlines. *The first systems will be decommissioned in the near future, with the second ones then upgraded to higher repetition rates or energy outputs (depending on the systems).*
MULTI-NANO (BE)	The Hofkens lab (MULTI-NANO) applies a set of different instruments (super-resolution imaging, ultrafast spectroscopy, scanning probe microscopy, correlated imaging, etc.) on a wide variety of timely and societal relevant topics.
MUT-IOE (PL)	The Institute of Optoelectronics at the Military University of Technology (MUT-IOE) is a leading research institution on laser development and application in Poland. Specific areas of research activity in the field include laser optics and electronics, laser systems, laser-matter interactions, laser ranging and sensing, nanotechnology and biomedicine. The Laser-Matter Interaction group has developed several experimental setups and workstations based on laser-plasma soft x-ray and EUV sources obtained from 1-10 ns / <10 J laser irradiation of a gas puff target at 10 Hz. The setups and workstations have been applied in various fields, including soft x-ray and EUV microscopy and tomography, EXAFS, processing materials with EUV photons, soft x-ray and EUV radiation damage, modification of biomaterials, EUV photoionized plasma studies, metrology of soft x-ray and EUV optical elements and detectors, and others.
NFFA-Trieste/ SPRINT (IT)	The Spin Polarized Research Instrument in the Nanoscale and Time (SPRINT) at the Nanoscience Foundries & Fine Analysis in Trieste (NFFA-Trieste) offers users two workstations: - a high-order harmonic beamline (17-31 eV / 100 fs [200 kHz]) coupled to OPA pumps (210 nm-1.6 µm / 200 fs and 630 nm-2.5 µm / 30-50 fs), a vectorial Mott detector and a high-resolution (22 meV) hemispheric electron analyser (suited to time-resolved valence band PES and spin detection) for the study of ultrafast magnetic processes in solid-state matter - a four-wave-mixing, magnetoelastic transient grating, setup (combining two µJ / <300 fs laser pulses at 1.03 µm and 515 nm [50 kHz-1 Mhz]) for the generation and detection of optical and acoustical phonons in magnetic materials. *A new setup for time-resolved Raman spectroscopy will be soon available.*
QUB/TARANIS (GB)	TARANIS, an Nd:glass facility at the School of Mathematics and Physics of the Queen's University of Belfast (QUB) delivers two optically-synchronised pulses at a repetition rate of 1 shot per minute: 20 TW ⬀ *60 TW* / 0.5 ps and/or 30 J ⬀ *80 J* in the ns regime. The facility is equipped with two target areas, the first one dedicated to high-intensity laser-matter interaction – and to the development and applications of secondary sources – and the second to the study of high-energy ns laser-matter interaction. *A kHz, fs, mJ source is currently being developed to complement the facility.*

SMARTLIGHT (FR)	*In around five years, SMARTLIGHT will become a research and innovation platform with key facilities to develop the next generation of smart photonic technologies and place machine learning at the heart of light science. The platform will implement a set of innovative scientific equipment, structured around four interdependent themes: high-speed real-time optoelectronic devices, ultra-short reconfigurable laser, multimodal optical microscopy and 3D printer for photonic connections.*
Sofia U./FSLAB (BG)	The Laboratory of Femtosecond Photonics (FSLAB) at the Sofia University is the first femtosecond photonics facility in Bulgaria and on the east Balkans. The TiLight oscillator (Ti:sapphire – 2.5 mJ / 25 fs [1 kHz]) allows the study of laser-matter interaction and high harmonics generation. Other additional (cw tunable Ti:sapphire, cw and ns diode-pumped and He-Ne) laser sources are available. *A new sub-7-fs Ti:Sapphire laser equipped with a CEP stabilisation module will be soon in operation.*
SCSTI/ILC (SK)	The International Laser Center (ILC) of the Slovak Centre of Scientific and Technical Information (SCSTI) offers access to a whole set of laboratories and techniques on information technology, laser micro-technology (PLD, surface marking and drilling, micro-welding), secondary ion mass spectrometry, applied optics, material and surface analysis (field-emission SEM, AFM, STM), fs spectroscopy (including THz spectroscopy and FLIM) or cell biophotonics, etc. *An upgrade of the full-scale access-providing infrastructure for imaging, spectroscopy and time-resolved techniques utilising advanced laser sources is foreseen.*
ULF-FORTH (GR)	The Ultraviolet Laser Facility (ULF-FORTH) is a multi-disciplinary laboratory dedicated to laser-based science. It is the major laser research facility in Greece. A series of laser sources are available: - several Ti:sapphire laser sources including a 17.5 TW / 20 fs [10 Hz] or 3 mJ / 25 fs [1 kHz] one and a new dual-beam fs oscillator [650-1350 nm and 1040 nm] - a Nd:YAG-dye laser source (2 mJ / 10 ns / 400 nm-4 µm [10 Hz]), - a KrF laser source (10 mJ / 150 fs-450 fs-5 ps [1-10 Hz]), - tunable visible-UV-VUV low-energy laser sources (220-1800 nm / 5-20 ns) and a new dye-OPA NIR system tunable from 400 nm to 4 µm. These laser sources allow the generation of secondary sources, from tunable XUV (55-115 nm) high-flux (10^{5-11} ν/pulse) photon sources to UV-NIR and 0.11-10 THz radiation sources. ULF-FORTH offers workstations for 2D and 3D micro/nano-processing, subtractive and additive manufacturing, material characterisation (XRD, TEM, SEM, etc.), ultrafast time-resolved spectroscopy and biophotonics (integrating live cell microscopy, non-linear imaging, cellular manipulation and bioprinting), as well as a series of characterisation techniques (amongst which: SHIM, MPM, fluorescence molecular tomography, slice imaging, photoacoustic imaging and coherent Raman microscopy).
ULLC (LV)	The Laser Centre of the University of Latvia (ULLC) is the largest laser laboratory in Latvia. Its researchers work in the areas of atomic, molecular, chemical physics and astrophysics, as well as in the application of laser techniques, such as FLIM, OCT, Raman spectroscopy and B-field imaging microscopy or magnetometry using diamond NV centres.
USZ/HILL (HU)	The High Intensity Laser Laboratory (HILL) at the University of Szeged operates a high-intensity femtosecond hybrid dye/excimer laser system offering the best **laser parameters at 248 nm in Europe** (100 mJ / 600 fs coupled to 60 mJ / 150 fs [10 Hz]) for research projects in plasma physics, solid-state physics and material micro-processing. *Improvements of the temporal and spatial contrasts and of the output energy (through multiplexing) are foreseen as well as the commissioning of a new ArF laser source at 193 nm.*
USZ/TeWATi (HU)	The TeraWattTitan-saphire laboratory of the University of Szeged hosts a TW-class laser system in the Central European region. After the recent upgrade, the major laser system based on positively chirped pulse amplification (NPCPA) runs at 100Hz repetition rate. The few cycle output provides pulses with 9.2fs and 0.3mJ, while the power output supports 26fs pulses with 36mJ. Development of high repetition rate target systems, femtosecond material processing, and laser-induced X-ray imaging are among the applications. A second, independent Ti:S system with 40 fs, 2 mJ pulses up to 50 Hz repetition rate is used mainly for trainings, educations and student experiments.

VULRC (LT)	Vilnius University Laser Research Center (VULRC), where the **first proof-of-concept experiment on OPCPA** was conducted in the 90s, hosts a series of laboratories dedicated to fundamental and applied laser research in a **strong industrial environment**. A large number of laser sources is available: Yb:KGW (0.1 mJ / <300 fs / 1350-2900 nm [200 kHz]), Ti:sapphire OPA (50 μJ / 50-100 fs / **computer-assisted tunability from 240 nm to 13 μm** [1 kHz]), Yb OPA (0.4 mJ / 210 fs [1 kHz-1 MHz]), Nd:YAG (<30 W / sub-ns and ns [Hz-kHz]) and Ti:sapphire (<10 mJ [kHz]). The list of laser-based techniques offered for advanced spectroscopy and imaging, nonlinear optics, material processing, light-matter interaction at direct laser writing 3D lithographic fabrication conditions and microfluidics is impressive.
Wigner RCP/ FemtoLab (HU)	The Ultrafast Nanooptics Research Group (FemtoLab) at the Wigner Research Centre for Physics operates a series of Ti:sapphire oscillators OPAs – among them: 7 mJ / 35 fs [1 kHz], 0.4 mJ / 35 fs [10 kHz], 260 nJ / 60 fs [3.6 MHz] and 2.5 nJ / 5 fs [80 MHz] – and harmonic radiation sources for, for example, studies of ultrafast phenomena in condensed systems and nanostructures, nano-optics and plasmonics, using, for instance, TOF setups, hemispheric spectroscopy or retarding potential electron spectroscopy.

Free-electron laser RIs

CLIO (FR)	The Centre Laser Infrarouge d'Orsay (CLIO) is a platform operating a pulsed free-electron laser continuously tunable between 2.5 and 150 μm and delivering pulses of duration adjustable from 5 to 10 ps at 62 MHz. It can lase simultaneously at two different, independently tunable, frequencies, allowing two-colour pump-probe experiments. The FEL is distributed into three user stations for SFG, IRMPD and AFMIR (a novel technique developed at CLIO). Additional optical laser sources are available to users (in the UV – at 266 nm, coupled to ion traps – or in the IR range thanks to OPOs operating in the 2.5-5 μm range in the ns regime). *Replacement of the klystron is scheduled thanks to a 2022 grant from the Paris-Saclay University.*
European XFEL (DE)	The European X-ray Free Electron Laser (XFEL) is an ESFRI landmark providing scientists from all over the world with ultrashort x-ray flashes – with a brilliance a billion times higher than that of the best conventional x-ray radiation sources – that will open up completely new research opportunities for scientists and industrial users. The FEL is operated in a SASE mode and the <25 fs-long x-ray flashes (27,000 pulses/s) are distributed to three beamlines – SASE1 and SASE2 (0.05-0.4 nm), SASE3 (0.4-4.7 nm) – and six experimental stations: - FXE for ultrafast dynamics in the condensed phase (XRD, XDS, wide-angle x-ray scattering, XAS, XES, RIXS, XANES, EXAFS) - SPB/SFX for 3D diffractive imaging and 3D structure determination of μm-scale and smaller objects, at atomic or near-atomic resolution (single-particle CDI, SFX) - MID for material science (CDI, XPCS, x-ray angular correlation analysis, x-ray speckle visibility spectroscopy, x-ray wide/small-angle scattering) - HED for high-energy-density science (PCI, XRD, IXS, XAS, XMCD) This unique scientific instrument includes a pulsed laser heated DAC setup and allows the generation of matter under extreme conditions of pressure, temperature or electric field using the FEL radiation, *pulsed magnets* and the HiBEF laser sources: the 5 Hz CPA Ti:sapphire laser source ReLAX 3 J / 25 fs *and soon the 10 Hz Yb:YAG laser source DiPOLE100-X 100 J / 2-10 ns.* - SQS for investigations of fundamental processes of light-matter interaction in the gas phase (electron- and ion-TOFs, VMI, COLTRIMS, MBES, RIXS) - SCS for time-resolved experiments to unravel the electronic and structural properties of complex materials, molecules, and nanostructures in their fundamental space-time dimensions (XRD, RIXS, MHz spectroscopy) - SXP for studying dynamics of materials science at surfaces and interfaces (time-resolved XPES). Additional low-energy optical laser sources are available at each experimental station. *Foreseen upgrades include new source functions (variable polarisation and attosecond duration) as well as additional beamlines (SASE4 and SASE5) – serving four new instruments – and implementation of superconducting undulators to allow delivery of harder photons (from 30 to 80 keV).*

FELIX (NL)	The user facility FELIX (Free Electron Lasers for Infrared eXperiments), operated by the Radboud University, provides the scientific community with tunable radiation of high brightness in the mid- and far-infrared as well as the THz regime. The facility houses two independent accelerators that together drive four FELs delivering linearly polarised 0.3-5 ps pulses at 1000 MHz: - FEL-1: 20-150 µm - FEL-2: 2.7-45 µm - FELICE: 3-100 µm - FLARE: 100-1500 µm The infrared beam lines are coupled to more than a dozen user laboratories, covering sophisticated instrumentation for experiments in the areas of molecular and biomolecular spectroscopy, cluster sciences, time-resolved spectroscopy or laser spectroscopy, while the intracavity molecular beam instrument on FELICE is used for spectroscopy of strongly bound clusters and ions. Additional low-energy optical laser sources are available to users as well as a set of techniques, including: electron and ion-TOFs, Ramsey spectroscopy, IR-UV double resonance dissociation spectroscopy, ion trap mass spectrometry, FTICR, EPR and IRMPD. World-unique is the combination of the infrared and THz radiation with quasi-continuous high magnetic fields (up to 38 T dc magnetic field) of the High-Field Magnet Laboratory (HFML). *FELIX is planning an upgrade, with a wavelength extension, the study of pulsing schemes, the upgrade of existing instruments and a new beamline switchyard.*
FERMI (IT)	Unique amongst the only five FEL sources currently operating in the ultraviolet and soft x-ray range worldwide, FERMI (Free Electron laser Radiation for Multidisciplinary Investigations) at Elettra Sincrotrone Trieste has been developed to provide fully coherent ultra-short seeded pulses – with variable polarisation and a peak brightness ten billion times higher than that made available by third-generation light sources – delivered by two beamlines: FEL-1: 20-100 nm (50-100 fs) and FEL-2: 4-20 nm (20-60 fs), at 10-50 Hz. FERMI is opening opportunities for the exploration of the structure and transient states of condensed matter, soft matter and low-density matter using a variety of instruments: DiProI (diffraction and projection imaging), EIS-TIMEX (absorption and elastic scattering from materials under extreme conditions), EIS-TIMER (inelastic and transient grating spectroscopy), LDM (gas phase and cluster spectroscopy), TeraFERMI (THz spectroscopy) and MagneDyn (magneto-dynamical studies). Electron- and ion-TOF, MBES, VMI and CDI techniques are also available, as well as a CPA Ti:sapphire laser (<1 mJ / 80-250 fs) for pump-probe experiments. *An upgrade is planned on FERMI (FERMI2.0); it aimed at extending the emission spectral range of FEL-2 to the water window and allowing pulse durations below the characteristic lifetime of atomic core holes in this energy range. New features will also include laser and FEL light pulses with orbital angular momentum.*
DESY/FLASH (DE)	FLASH, the Free-Electron Laser in Hamburg, operated by DESY in the SASE mode, was the first free-electron laser for XUV and soft x-ray radiation. FLASH1 delivers 4.2-51 nm pulses with duration <30-200 fs, while FLASH2 delivers 4-90 nm pulses with duration <10-200 fs, both at 5 kHz. In addition, it is possible to produce THz pulses (10-230 µm) fully synchronised with the FLASH1 soft x-ray pulses. Additional laser sources (Ti:sapphire: 10 mJ / 60 fs [10 Hz] and Yb:doped: 20 µJ / 100 fs [10 kHz]) for FLASH1, OPCPA: 200 µJ / <100 fs / 700-900 nm [1 kHz] for FLASH2) are available to users, as well as techniques such as VMI, COLTRIMS, electron- and ion-TOFs, THz spectroscopy and RIXS. The FLASH user facility is complemented by chemistry labs and a S2-biolaboratory, as well as by the DESY NanoLab for sample preparation respectively characterisation before the beamtime. *Four additional endstations will be commissioned on FLASH2 and the whole FLASH facility will be upgraded through the FLASH2020+ project. One of the two FEL lines shall be fully externally seeded with the full repetition rate that FLASH can provide in burst mode. The other line will exploit novel lasing concepts based on variable undulator configurations. Together with a small increase in electron beam energy to 1.35 GeV this will extend the wavelength reach of the fundamental harmonics to the oxygen K-edge, in order to cover the important elemental resonances for energy research and the entire water window for biological questions.*

HZDR/ELBE (DE)	Operated by HZDR, the free-electron-laser facility FELBE relies on the superconducting linear accelerator ELBE, operating in cw mode with a 13 MHz repetition rate, to serve two FEL beamlines – U37 (5-40 µm / 1-10 ps) and U100 (18-250 µm / 3-30 ps) – and several user laboratories. Techniques such as optical sideband generation, time-resolved photoluminescence, magneto-spectroscopy, IRS, SNOM, s-SNIM *and soon ARPES*, as well as additional synchronised Ti:sapphire laser sources (OPA for extended wavelength range) for pump-probe experiments, are made available to users. Feeding the high-brilliance IR radiation from the free-electron laser facility FELBE to the Dresden High Magnetic Field Laboratory (HLD) pulsed magnetic field cells (up to 95T in 10ms) enables unique high-field magneto-optical experiments. In addition to the FELBE facility, HZDR operates TELBE, a high-field high-repetition-rate (10-500 kHz) THz facility, which delivers low-frequency, CEP-stable 150-3000 µm / 5-100 ps pulses for probing ultrafast terahertz-induced dynamics in various states of matter with highest precision.
MAXIV/SXL (SE)	*At the MAXIV Laboratory, an upgrade project, consisting of a soft x-ray Free Electron Laser (SXL), has been initiated. The project targets radiation in the 1-5 nm range in short (1-15 fs) pulses and assisted by a wide range of pump-probe sources, from THz to x-rays. The project builds on the accelerator infrastructure already in operation, a 3 GeV linear accelerator.*
PSI/SwissFEL (CH)	The compact X-Ray Free-Electron Laser Facility SwissFEL, at the Paul Scherrer Institut (PSI), is a new generation of light source, offering novel experimental capabilities in diverse areas of science by providing very intense and tightly focused x-ray pulses to explore structures as small as atoms and phenomena as fast as the vibrations of molecular bonds. The RI has two x-ray beamlines: - ARAMIS in the hard x-ray range (0.1-0.7 nm) operated in SASE or self-seeded modes and delivering single, linearly polarised, 13 fs pulses at 100 Hz - ATHOS in the soft x-ray range (0.65-5 nm) operated in a SASE mode and delivering single 11 fs pulses at 100 Hz with variable polarisation. These currently serve three experimental stations, the first two on ARAMIS, the third one on ATHOS: - ALVRA for studying ultrafast dynamics of photochemical and photo-biological systems using a variety of x-ray scattering and spectroscopic techniques (SFX, XDS, XAS, XES, IXS, HEROS) - BERNINA for studying ultrafast phenomena in condensed matter systems (XRD) - MALOJA for studying atomic, molecular and non-linear X-ray physics and chemical dynamics (COLTRIMS, TAS, XRD, hemispherical electron analyser, ion-TOF). Additional optical Ti:sapphire laser sources (OPA and nonlinear conversion for extended wavelength range) are available to users for pump-probe experiments. *The upgrade of the ATHOS beamline, in the framework of the HERO (Hidden, Entangled and Resonating Orders) project, aims to implement the echo-enabled high-harmonic generation technique to obtain the first fully coherent, externally seeded, soft x-ray FEL. In addition, two new experimental stations will be added to the RI: CRISTALLINA on ARAMIS, for imaging of quantum many-body states under extreme conditions and serial femtosecond protein crystallography; and FURKA on ATHOS, for the study of quantum materials using time-resolved RIXS and REXS, as well as XAS.*
POLFEL (PL)	*The Polish free electron laser (POLFEL) will provide tunable coherent electromagnetic radiation in the range of several nms (soft x-rays) to several hundred µms (THz). Several experimental systems designed to operate in the appropriate ranges of wavelength will be required to exploit the experimental possibilities fully.*
STAR (IT)	*The Southern Europe Thomson Back-Scattering Source for Applied Research (STAR) aims to offer advanced scientific investigation services in the field of fundamental and applied research on materials. It will be equipped with a powerful new concept of a 30-85 keV, 100 Hz x-ray source (based on Thomson backscattering) equipped with an experimental microtomography station which, through the acquisition of 3D images at very high resolution, will allow the examination of the internal structure of materials. Two beamlines are being built: SoftX, at low energy, for investigations on biological, polymeric and composite materials, and µTomo, at high energy, for materials used in the sectors of mechanics, electronics and cultural heritage.*

Glossary

AAS	atomic absorption spectroscopy
AES	atomic emission spectroscopy
AFM	atomic force microscopy
AFMIR	atomic force microscope-infrared (spectroscopy)
AOSLO	adaptive optics scanning laser opthalmoscopy
ARPES	angle-resolved photo-emission spectroscopy
CARS	coherent anti-Stokes Raman scattering
CDI	coherent diffractive imaging
CEP	carrier-envelope phase
COLTRIMS	cold target recoil-ion momentum spectroscopy
CPA	chirped pulse amplification
CRDS	cavity ring down spectroscopy
DAC	diamond anvil cell
EBS	enhanced backscattering spectroscopy
EDX	energy-dispersive x-ray (spectroscopy)
EELS	electron energy loss spectroscopy
EPR	electron paramagnetic resonance (spectroscopy)
EXAFS	extended x-ray absorption fine structure
FCS	fluorescence correlation spectroscopy
FDI	Fourier-domain interferometry
FEL	free electron laser
FLIM	fluorescence-lifetime imaging microscopy
FLUPS	fluorescence up-conversion spectroscopy
FRET	fluorescence energy transfer (microscopy)
fs	femtosecond (10-15 s)
FSRS	femtosecond stimulated Raman scattering
FTICR	Fourier-transform ion cyclotron resonance (mass spectrometry)
HEROS	high energy resolution off-resonant spectroscopy
ICP-OES	inductively coupled plasma optical emission spectroscopy
IRMPD	infrared multiple photon dissociation (spectroscopy)
IR	infrared
IRS	infrared spectroscopy
IXS	inelastic x-ray scattering
LCSM	laser confocal scanning microscopy
LEED	low-energy electron diffraction
LIBS	laser-induced breakdown spectroscopy
LIDAR	light imaging detection and ranging
LIDT	laser-induced damage testing
LIED	laser-induced electron diffraction
LIF	laser-induced fluorescence
LIFT	laser-induced forward transfer
LPI	laser-plasma interaction
LSFM	light sheet fluorescence microscopy
MBES	magnetic bottle electron spectrometry
MOKE	magneto-optic Kerr effect
MPM	multiphoton microscopy
nano-FTIR	nanoscale Fourier-transform infrared (spectroscopy)
NICE-OHMS	noise-immune cavity-enhanced optical-heterodyne molecular spectroscopy
NOPA	non-collinear optical parametric amplification

ns	nanosecond (10-9 s)
OAM	orbital angular momentum
OCT	optical coherence tomography
OPA	optical parametric amplification
OPCPA	optical parametric chirped-pulse amplification
OPO	optical parametric oscillator
PALM	photo-activated localisation microscopy
PEEM	photo-emission electron microscopy
PCI	phase contrast imaging
PLD	pulsed laser deposition
ps	picosecond (10-12 s)
PW	petawatt (1015 W)
REMPI	resonance-enhanced multiphoton ionisation (spectroscopy)
REXS	resonant elastic x-ray scattering
RGA	residual gas analyser
RICS	raster image correlation spectroscopy
RIXS	resonant inelastic x-ray scattering
SASE	self-amplified spontaneous emission
SEM	scanning electron microscopy
SFG	sum frequency generation
SFX	serial femtosecond crystallography
SHIM	second-harmonic imaging microscopy
SIM	structured illumination microscopy
SNOM	scanning near-field optical microscopy
SOP	streaked optical pyrometry
SRS	stimulated Raman scattering
s-SNIM	scattering scanning near-field infrared microscopy
STED	stimulated emission depletion (microscopy)
STM	scanning tunneling microscopy
STORM	stochastic optical reconstruction microscopy
TAS	transient absorption spectroscopy
TCSPC	time-correlated single-photon counting
TCT	transient current technique
TDRS	time-domain reflectance spectroscopy
TEM	Transmission electron microscopy
TIRFM	Total internal reflection fluorescence microscopy
TOF	time-of-flight (spectrometry)
trELIps	time-resolved ellipsometry
TRMPS	time-resolved multiple-probe spectroscopy
UED	ultrafast electron diffraction
VISAR	velocity interferometry system for any reflector
UV	ultra-violet
VMI	velocity map imaging
XAFS	x-ray absorption fine structure spectroscopy
XANES	x-ray absorption near-edge structure spectroscopy
XAS	x-ray absorption spectroscopy
XCT	x-ray computer tomography
XES	x-ray emission spectroscopy
XFEL	x-ray free electron laser
XMCD	x-ray magnetic circular dichroism
XPCS	x-ray photon correlation spectroscopy
XPES/XPS	x-ray photoelectron spectroscopy
XRL	x-ray laser
XRS	x-ray Raman scattering
XRD	x-ray diffraction

Laserlab-Europe Office, Max-Born-Str. 2A
12489 Berlin, Germany
office@laserlab-europe.eu

ELI ERIC, Za Radnicí 835
252 41 Dolní Břežany, Czechia
info@eli-laser.eu

Scientific editor: Sylvie Jacquemot