IMPULSE

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Report on "Laser Science and Technology Roadmap for Europe"

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Abstract:

Laserlab-Europe and the Extreme Light Infrastructure ERIC have jointly launched surveys to analyse the current laser- based science landscape in Europe. This analysis aims at broadly qualifying and quantifying the European laser community for a better understanding of the services offered to users by Research Infrastructures (RIs) operating laser sources, today and in the near/medium future, and of the user needs and requirements. The consolidated report gives an overview of the complex landscape and allows identifying complementarities, aligning efforts and defining high-level objectives.

IMPULSE has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871161.

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1 Introduction

Laserlab-Europe and the Extreme Light Infrastructure ERIC have joined forces to analyse the current laser- based science landscape in Europe. This analysis aims at broadly qualifying and quantifying the European laser community for a better understanding of the services offered to users by Research Infrastructures (RIs) operating laser sources, today and in the near/medium future, and of the user needs and requirements. The consolidated report gives an overview of the complex landscape and allows identifying complementarities, aligning efforts and defining high-level objectives. It provides data for European-level political consultations, for which the importance of national RIs is often overlooked in view of the focus on ESFRI RIs and ERICs, and supporting any discussion – with the European Commission and with national agencies – about sustainable funding for RIs through the provision of factual and up-to-date information.

Milestone 73 outlined initial Guidelines for the Science and Technology Road-mapping For the European Laser Community.

1.1 Objectives

The main objective of the landscape analysis is to produce a consolidated report about the European laser community with the following goals:

- attain a big picture overview of the complex landscape of high energy high repetition laser-based research infrastructures in Europe with links to globally relevant research infrastructures,
- align efforts in the laser research infrastructure ecosystem, complementarity, and effective use of European laser facilities,
- anchor ELI ERIC within the laser community,
- define main high-level objectives for laser technology and themes of laser-based research revolving around laser technologies,
- improve and streamline communication across the laser community in Europe.

1.2 Target Groups of Survey

The main focus groups which the research will be based on will be the following:

- Laser Facilities with a focus on high-intensity and high-repetition laser technology
- Scientific and academic users
- Industrial users
- Stakeholders and decision makers
- Actors in the innovation ecosystem

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3 Implementation

Laserlab-Europe and the Extreme Light Infrastructure ERIC collaborated in developing and launching two surveys targeting the RIs the user community. The first survey targeted laser RIs to understand their services, and the second survey targeted the user community to identify their needs. The survey results were analysed and an initial outline developed with the support of a group of representatives from Laserlab-Europe facilities and ELI. Initial conclusions were presented during a side event at the International Conference for Research Infrastructures (ICRI). Based on this presentation an extended report was developed which is presented in the Annex I.

Annex 1 lays out the current status of the European laser landscape and provides valuable insights into the European Laser RI Landscape and its strengths and challenges. By highlighting the importance of collaboration, standardization, 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 be valuable for decision-makers, stakeholders, and the wider laser RI community in ensuring the growth and sustainability of this critical field.

4 Annex I – European Laser Science and Technology Landscape

IMPULSE has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871161.

European
Laser Science and Technology
Landscape & Roadmap

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


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Foreword

Laserlab-Europe and the Extreme Light Infrastructure ERIC have joined forces to analyze the current laser-based science landscape in Europe. This analysis aims at broadly qualifying and quantifying the European laser community for a better understanding of the services offered to users by Research Infrastructures (RIs) operating laser sources, today and in the near/medium future, and of the user needs and requirements. The consolidated report gives an overview of the complex landscape and allows identifying complementarities, aligning efforts and defining high-level objectives. It provides data for European-level political consultations, for which the importance of national RIs is often overlooked in view of the focus on ESFRI RIs and ERICs, and supporting any discussion – with the European Commission and with national agencies – about sustainable funding for RIs through the provision of factual and up-to-date information.

Laserlab-Europe unites 46 leading organizations 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 in the framework of 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 – represent the highest concentration of world-class 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 end stations and enable 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 focuses on achieving a quick and effective transition 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

The following European “Laser RI Landscape” is a joint analysis conducted by Laserlab-Europe and Extreme Light Infrastructure ERIC (in the context of two European projects sponsored within the Horizon 2020 framework programme). The aim is to provide an overview of the European laser community, understand the services offered by the research infrastructures and user needs, and provide data for political consultations at the European level.

The laser RI landscape analysis methodology was based on a “think-tank” approach, followed by two surveys. The first survey targeted laser RIs to understand their services, and the second survey targeted the user community to identify their needs. The European laser landscape is diverse in services, ranging from primary to secondary sources covering the electromagnetic spectrum from x-rays to THz and including particle sources. A wide variety of instruments and techniques complement the various laser sources. Access to the RI facilities includes dedicated support and expertise from local teams. The survey results suggest a need for a sustainable European laser RI ecosystem, improved access to facilities, and increased collaboration.

The impact of laser-based instruments is broad.

In the energy sector, lasers contribute to developing clean energy technologies such as solar cells, smart materials, and laser fusion. Laser-based techniques provide vital insights into the underpinning mechanisms to engineer efficient solar cells and process them. Similarly, new quantum materials are investigated with ultrafast laser techniques to address the increasing energy consumption of consumer electronic devices. Recent developments in the United States have scientifically demonstrated the physics of laser-based fusion. Further developments in laser-based techniques in the energy sector in Europe are needed for a sustainable and economic environment.

In the health sector, lasers have long had a major impact, revolutionizing eye surgery and treatment. Today, lasers are utilized with microscopy techniques for instant diagnosis of cancerous and benign tumors, for angioplasty surgery and wound cauterization. They are also being used in in vivo diagnostic techniques and photodynamic therapy. Additionally, laser-accelerated ultrashort secondary sources have the potential to change the landscape of radiation oncology.

In space, lasers are being used in various applications, including laser-guide stars to correct atmospheric aberrations of images and laser-based frequency combs to find exo-planets. Optical technologies and lasers power the future generation of atomic clocks for global positioning and monitoring of the environment and international communication. High-power lasers are being developed for laser orbital debris removal. However, engineering challenges still need to be addressed for the latter to be used from satellites to ground stations.

For our environment, lasers are utilized for the sensitive and accurate detection of environmental pollutants and microplastics. They are essential to improve meteorological predictions and climate models, and they allow to track livestock.

Lasers in manufacturing lead to a significant reduction of chemicals, a significant reduction of energy consumption and hazardous waste. The replacement of traditional manufacturing techniques with modern laser processing reduces surface contaminants and greenhouse gas emissions. Lasers provide non-destructive methods for quality control and the security of food items.

Lasers are utilized in cultural heritage to study and protect cultural heritage artifacts. They are non-invasive and thus have a significant role in the field. For instance, photoacoustic imaging has been used to image preparatory underdrawings. At the same time, laser-induced breakdown spectroscopy (LIBS) was developed for surface cleaning to preserve art, for instance, the west frieze of the Parthenon in Athens.

Findings and Recommendations

The report found that the diversity of the European laser RI landscape is essential since it offers a wide range of services and access to tools and techniques for fundamental research, applications, and industrial services. Collaboration and support from technical and scientific teams are essential and highly valued by the user community. However, the report highlights that there are also challenges in standardization, coordination and funding, which need to be addressed to ensure the sustainability and global competitiveness of the laser RI ecosystem.

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

1. establishing a common strategy for laser RIs in Europe to better align efforts, enhance complementarities and increase synergies,
2. encouraging standardization and interoperability of laser RIs to improve efficiency, facilitate user mobility and ensure data compatibility,
3. securing long-term and sustainable funding for laser RIs to ensure their stability, growth, and competitiveness,
4. enhancing coordination between laser RIs and user communities to better understand 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 and its strengths and challenges. By highlighting the importance of collaboration, standardization, 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 be valuable for decision-makers, stakeholders, and the wider laser RI community in ensuring the growth and sustainability of this critical field.

Jens Biegert, Laserlab-Europe AISBL Executive Director

Sylvie Jacquemot, Laserlab-Europe Project Coordinator

Allen Weeks, ELI ERIC Director General & IMPULSE Project Coordinator

Introduction

Since the first working laser in 1960, lasers can be found everywhere in everyday life, in living rooms, supermarkets, medical offices or factories but also in research laboratories, where they have made themselves inescapable for a lot of disciplines.

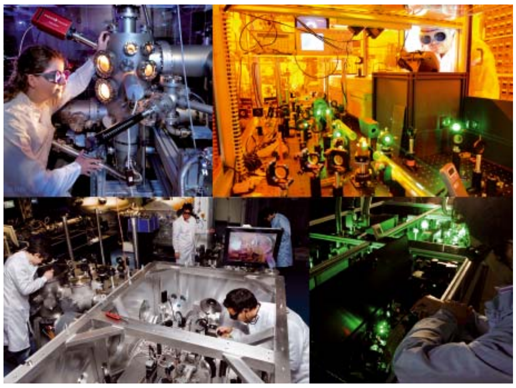
With their unique features, in terms of energy, duration, repetition rate or spectral coverage, above laboratory performances, laser research infrastructures (laser RIs) play a major role in advancing laser science and contribute to put Europe in the forefront of the field.

To maintain the European leading position, future strategic scientific, technological and innovation-related challenges with regard to laser science, technology and applications, must be timely anticipated. A strategic roadmap needs thus to be established in order to guide the next developments of the European laser RIs, from major upgrades of currently operational RIs to the commissioning of brand new facilities. Prior to such exercise, an accurate analysis of the existing landscape is required to get the most possible global perspective. The present report aims at presenting contributions to these two exercises.

Methodology

In order to conduct the laser RI landscape analysis, a comprehensive methodology was established, based on the creation of a think-tank and on two surveys.

The think-tank was composed of representatives of ELI ERIC, Laserlab-Europe and the user community. In order 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.



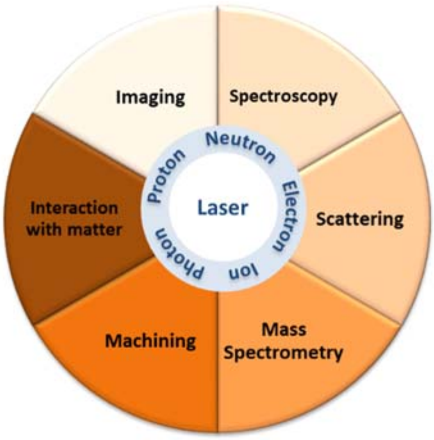
The first survey targeted laser RIs in order to get a better understanding of the services they are currently offering to users and how these services will evolve in the near to medium term. It was sent to all Laserlab-Europe members, the three ELIs, eight free-electron lasers (FELs) – members of the 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. The criteria for inclusion were that the facility has to be currently operational and open (at least partly) to external users. However, some RIs that will be commissioned soon have also been approached in order to be able to include them in the laser road-mapping exercise. The full list of the responding RIs is given in annex.

OUR IMPACT IS DRIVEN BY THE SUCCESS OF OUR USERS

The second survey targeted the Laserlab-Europe user community as well as the collaborators and potential users of the ELIs, given that the survey has been launched before the first ELI call for proposals. It identified the user needs to support further development of a suitable and effective European laser RI ecosystem, thus constituting an important building brick of the laser RI roadmap.

CURRENT LANDSCAPE OF LASER RESEARCH INFRASTRUCTURES IN EUROPE

Diversity of the laser RI landscape



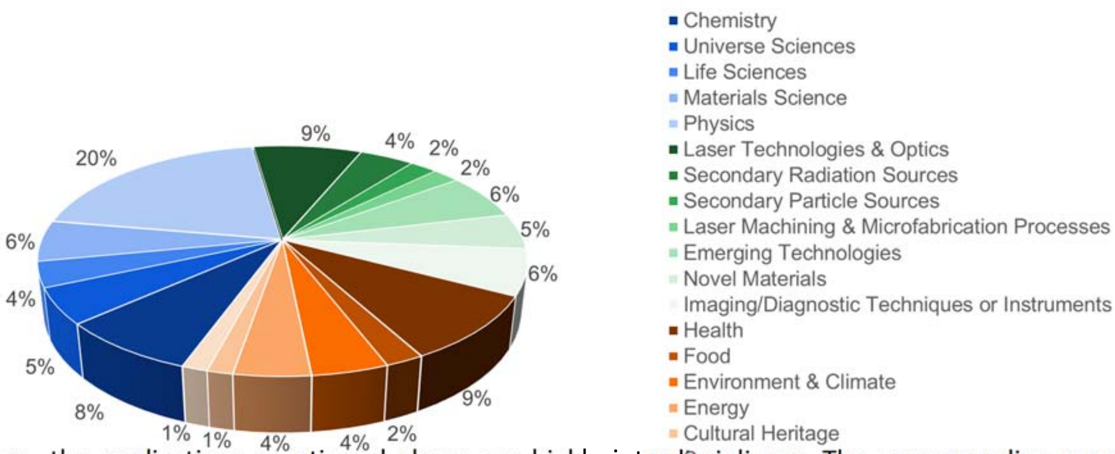
The European laser landscape is proven to be extremely diverse, first in terms of services offered to users, being not only restricted to laser photon providers. The facilities allow providing access from primary laser sources to secondary sources[1] – covering a wide range of radiation wavelengths and elementary particles – and to a variety of laser-based instruments and techniques.

However, access is not limited to the provision of access to tools and techniques but encompasses a strong collaborative component. A very large majority of the RIs offers support and expertise of their technical and scientific local teams, reflecting the needs of almost 90% of the users.

In addition, a complete environment is generally offered to the users, and greatly appreciated; it includes for instance mechanical workshops (for half of the RIs), biology / cell culture laboratories – up to biosample management and handling – or target laboratories (for one third of the RIs), and cryogenics (~20% of the RIs). The concept of targetry covers not only solid targets, usually required for laser-matter interaction, but also gas/cluster/liquid jets, chemicals, phantoms, etc. This series of additional support services should be duly advertized as it could encourage new users to apply for access and as it could be a specificity of the European laser RI community.

The diversity is also present in the scientific fields explored, from deepening fundamental knowledge – in chemistry, life science, 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.

A well-balanced support to knowledge-driven, R&D and society-driven user projects (with emphasis put on health) are provided by the RIs, even if they are personally prone to invest in the future, especially through the development of secondary sources for further applications and through the developments of novel laser technologies and instrumentation tools.

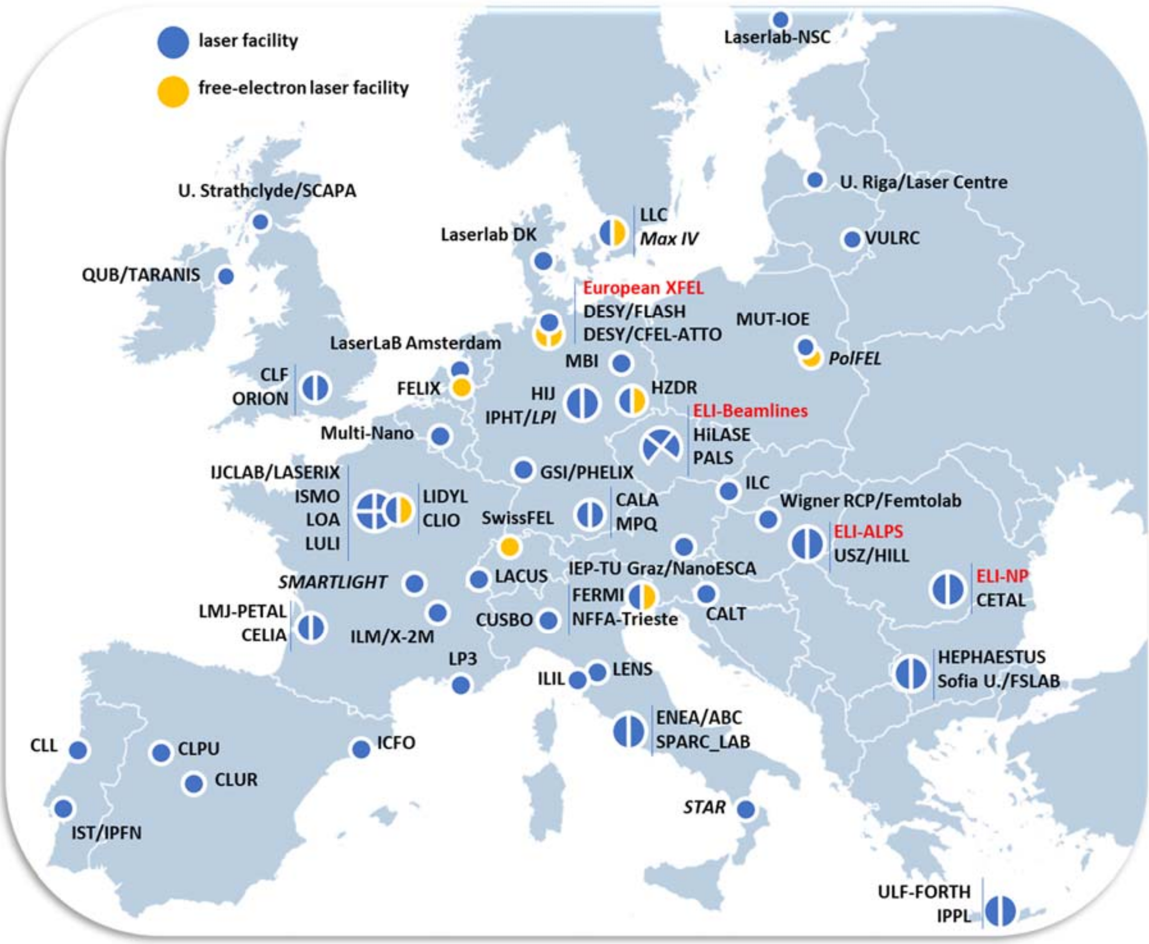


Furthermore, the applications mentioned above are highly interdisciplinary. The corresponding research activities hinge on knowledge accumulated in fundamental scientific disciplines and development of suitable

[1] The term "secondary source" designates a source of radiation or a beam of particles produced after interaction with matter (whatever its state) of a laser light source (thus referred as the primary source).

tools, which, both, help to fulfill the requirements to tackle societal challenges. For instance, environmental and medical applications are embedded in a very intricate landscape that connects different scientific disciplines (such as Life Sciences & Materials Science or Life Sciences & Chemistry) and technologies (especially devoted towards dedicated optimization of secondary sources). Such a complex panorama underlines the benefits of building a multidisciplinary network of instruments offering a wide variety of services and laser source parameters.

The diversity can finally be seen in the wide distribution of the laser RIs across Europe, with 23 countries hosting them, including 11 widening countries.

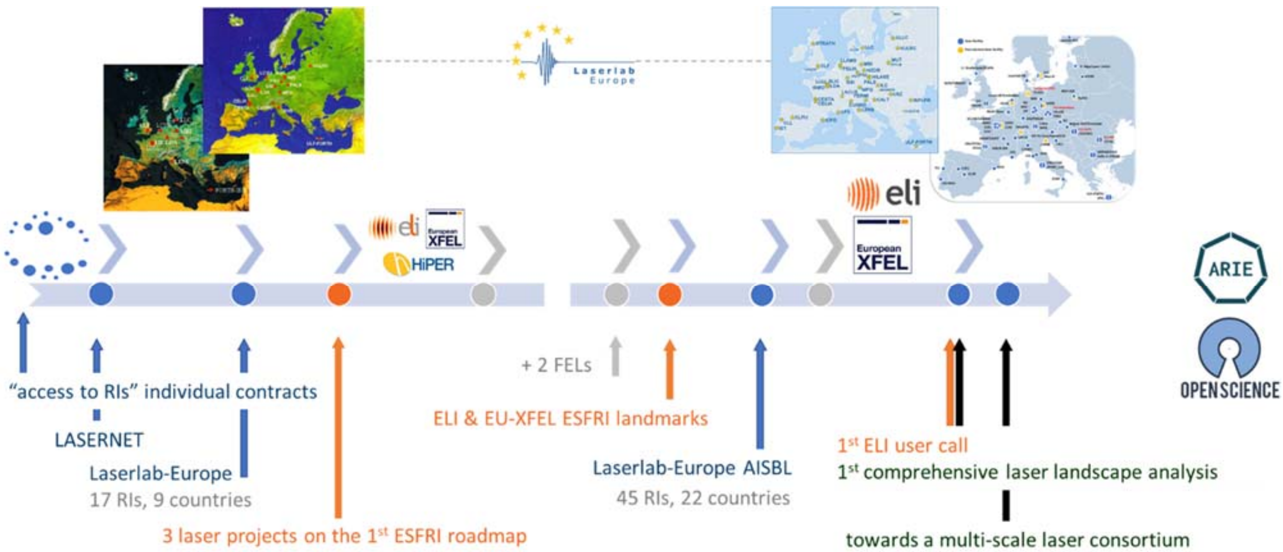


This constellation of very diverse facilities, from microscopy stations to ESFRI landmarks, is offering at each location, regardless the size of the facility, unique and high-quality services and expertise contributing to serve a broad user community. It is also building a coherent staged laser ecosystem, from highly accessible national instruments to ESFRI landmarks or world-class infrastructures, the coordination being ensured – for most of them – by Laserlab-Europe and ELI ERIC. In fact, the added value of such multi-scale ecosystem ensues from pilot studies conducted on small facilities feeding large-scale ones to enable cutting-edge frontier science and serve a broad user community, beyond the European borders, with 10% of international Laserlab-Europe individual users.

Capitalizing on complementarities and synergies to achieve integration

The European laser landscape is in constant evolution and the panorama presented above is a snapshot of the current situation. This situation is capitalizing on the complementarities and synergies to move from single entities, providing access from the 2nd to the 5th EU framework programmes under individual contracts, to a network – LASERNET – built to fight fragmentation and then to an European Distributed Infrastructure above national facilities – namely Laserlab-Europe – progressively expanding from 17 to 45 partners in order to offer to the user community an ever broader spectrum of capabilities, with for instance the inclusion of FELs in 2015. Along this route, Laserlab-Europe has supported the preparatory phase of 2 pan-European very-large-scale RIs: HiPER and ELI. The consortium has also gained sustainability with the establishment of the Laserlab-Europe AISBL in 2018.

The next step, starting with this landscape analysis, integrates the ELIs and prepares first a multi-scale laser consortium, once lasting transversal collaborations established, and then for further clustering with other analytical RIs. The ultimate transformation of the landscape will be induced by the adoption of the Open Science tenets, which requires modifying current scientific routines, developing suitable tools and implementing common regulations on ethics and professional integrity. Even if already engaged, these transformations – open science and closer integration – shall however be accepted by all the partners, which means that they have to be progressive and 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[2] and that it is largely supporting the market, which should reach close to 15 billion dollars by 2024.

However, a strong competition exists worldwide.

Following a 2017 report stating that the United States of America have lost its dominance in the field of high-intensity laser technology, the U.S. Department of Energy has established LaserNetUS, using Laserlab-Europe as a model, to improve the American competitiveness in high-intensity laser research. It has additionally heavily invested in facility upgrades and user support ($18 million for 3 years, from 2020). The ZEUS laser system at the University of Michigan was thus funded (to bring the US in the multi-petawatt world) as well as the upgrade of the “Matter in Extreme Conditions” instrument at the LCSLS XFEL, increasing its performances well above the ones 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 ever on Earth and exawatt laser projects are underway in China, Japan and Korea, engaging the European supremacy.

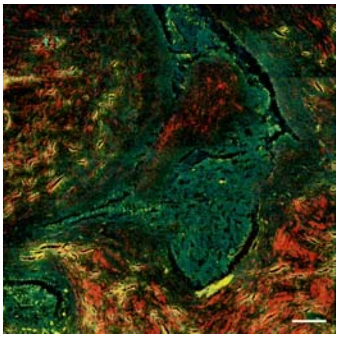
As a result of the reduction of the EC-supported transnational access units along the years, of the opening of the Laserlab-Europe programme to non-European users, and of the subsequent collaboration policy with the LaserNetUS and AILN networks (leading to the reciprocal opening of their calls to European users), the European users are more and more prone to target worldwide facilities to conduct their research. This tendency, observed before the COVID pandemic, should however be confirmed in the forthcoming years; if confirmed, the competitiveness of the European laser RIs should be reinforced through unique capabilities, such as the foreseen ELI ones.

[2] 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 KEY CONTRIBUTORS TO EUROPE GLOBAL CHALLENGES

The multiple facets of the European laser landscape, in terms of services and fields of research offered to and tackled by the user community, are a major asset to contribute to the European global challenges, fostering cross-disciplinarity and thus emergence of new ideas and breakthrough innovations. Whatever the laser landscape transformations may be, laser technology is proven to be a game changer for the future in many scientific, technological and societal areas.

- *Health*



[Sci. Rep. 10, 11055 (2020)]

Multimodal non-linear laser-based microscopy techniques have demonstrated their capabilities to discriminate benign from cancerous samples within seconds, far below the duration of a surgery. As other imaging modalities, they promise non-invasive diagnostic tools for reducing recalls and unnecessary biopsies or for providing instant feedback on the nature of an excised tissue. Polarization sensitive optical coherence tomography imaging was shown to be a promising as a minimally invasive diagnostic method to assess asthma-induced airway remodeling. Photoacoustic tomography is an emerging technique providing label-free non-invasive 3D structural and functional images of, e.g., vasculature. More generally, laser-based *in vivo* diagnostic techniques are simpler and cheaper than current traditional techniques; they complement these latter usefully, providing objective (operator-independent) functional information.

In addition to photodynamic therapy, which is now widely used to treat many conditions (including acne, serval cancers, psoriasis, etc.), laser-accelerated ultrashort secondary sources could also change the landscape of radiation oncology, taking advantage of unprecedented instantaneous high dose rates (of the order of gigaGy/s) delivered on sample. Recently, an important milestone has been achieved with the first-ever controlled in-vivo irradiation of mice tumors with laser-accelerated protons, which shows a clear radiation-induced effect.

- *Food*

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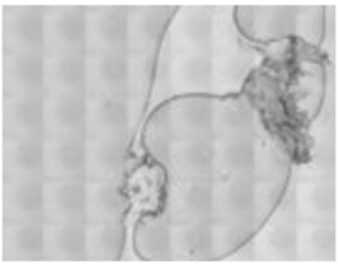
Lasers are at the basis of non-destructive methods for a variety of applications towards healthy and high-quality food. A technique was for instance developed for inline quality control of packed food items throughout the supply chain thanks to the non-intrusive measurement of the oxygen content in package headspace (supposed to be kept minimum). It is also possible to analyze 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.

- *Environment*



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Environmental needs could valuably be addressed thanks to sensitive and accurate laser detection of atmospheric pollutants (e.g. soot from biomass burning or engines) and microplastic pollutants. An innovative microscopy approach has, for instance, been conceived for a quick identification of the major types of polymer particles and successfully demonstrated in sediments from the Rotterdam harbor area while fluorescence imaging was employed to show that algae could be used to supervise water quality, tracking from pH modification to heavy metal presence. Laser diagnostic techniques allow also measuring temperature and species concentration in combustion systems, contributing to their optimization towards reduced emissions; it was thus shown that it could be possible to monitor – in real time – toxic organic by-products (such as dioxins) of incineration processes in order to ensure fast counteractions.

- *Energy*

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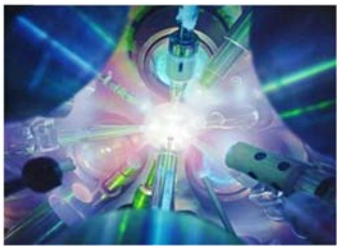
Lasers will also widely contribute to develop clean energy technologies, among them solar energy and laser fusion. They provide valuable insights into the fundamental processes occurring at ultrashort timescales in solar electricity generation, such as charge transfer processes in dye-sensitized organometal halide perovskite, solar cells, and contribute to find the best possible – cheap and flexible – materials to be used. Novel ultrafast coherent radiation sources are of special interest as they allow probing, in addition to fast dynamics, very small (at the sub-nanometer scale) structural changes. In addition, lasers can be used to functionalize materials thanks to multi-dimensional nanostructuring, thus contributing to energy storage, for example through the development of nanostructured electrodes for more efficient hydrogen production devices, fuel cells or batteries.



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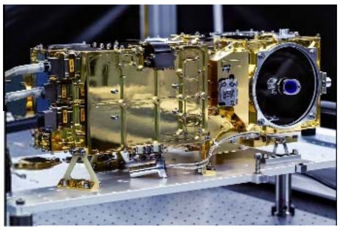
Laser fusion could also be envisioned as a clean and safe energy source, especially after the recent ignition achievement on the National Ignition Facility (NIF) in the US. However, further developments, both scientific and technological, are still required; while existing laser facilities will allow developing – at reduced scale – 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 transnational coordinated effort is necessary, as done by the magnetic fusion energy community with the ITER programme.

- *Space*



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Lasers start to be widely used in space. Laser-based techniques, such as LIBS coupled to Raman spectroscopy for the SuperCam instrument on board of the Perseverance Mars rover, are for instance useful for planetary exploration, allowing investigation of the elemental composition of soils and rocks and search for bio-signatures.

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Space debris threaten the use of the low Earth orbit space; removing them, whatever their size, is thus an urgent issue and a series of concepts has been already proposed, among them laser orbital debris removal. The required laser parameters to de-orbit or ablate the debris from ground or from space, determined from laser-matter interaction experiments conducted thanks to access to laser RIs, are still under investigation. A first step, which aims at tracking the debris very precisely thanks to laser pulses, has however been taken with, for instance, the ESA's IZN-1 Laser Ranging Station.

Allowing more data to be packed into a single transmission, laser communication in space is now widely used from satellites to satellites but efforts have still to be paid to solve engineering challenges (e.g. laser beam distortion due to atmospheric effects) to employ it from satellites to the ground stations since the first demonstration by Japan in 1995.

- *Industry*

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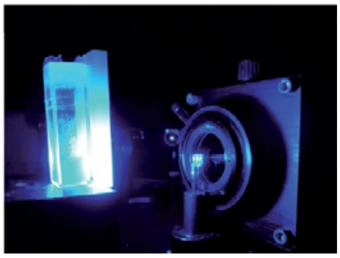
European RIs contribute to the understanding of the physics of laser-produced radiation sources for EUV lithography. The up-to-date 250W machines at 13.5nm are based on the interaction of a high-average-power laser with tin droplets, capitalizing on years of fundamental research on plasma physics. The next generation, which should rely to increase throughput on shorter wavelength (6.7nm) or higher power (kW), electrical consumption low, is under study. 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), for a wide variety of applications, in biomedicine, for embedded electronics, etc. In the case of metals, post-processes to improve the fatigue behavior of aerospace or medical products are currently developed to, e.g., induce compressive residual stresses deep in the material and, thus, increase resistance to crack initiation. A novel route combining laser lithography and thermal post-treatment was in parallel developed to enable additive manufacturing of crystalline ceramics at unprecedented precision (below 60nm) and 3D flexibility.

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

- *Safety & security*



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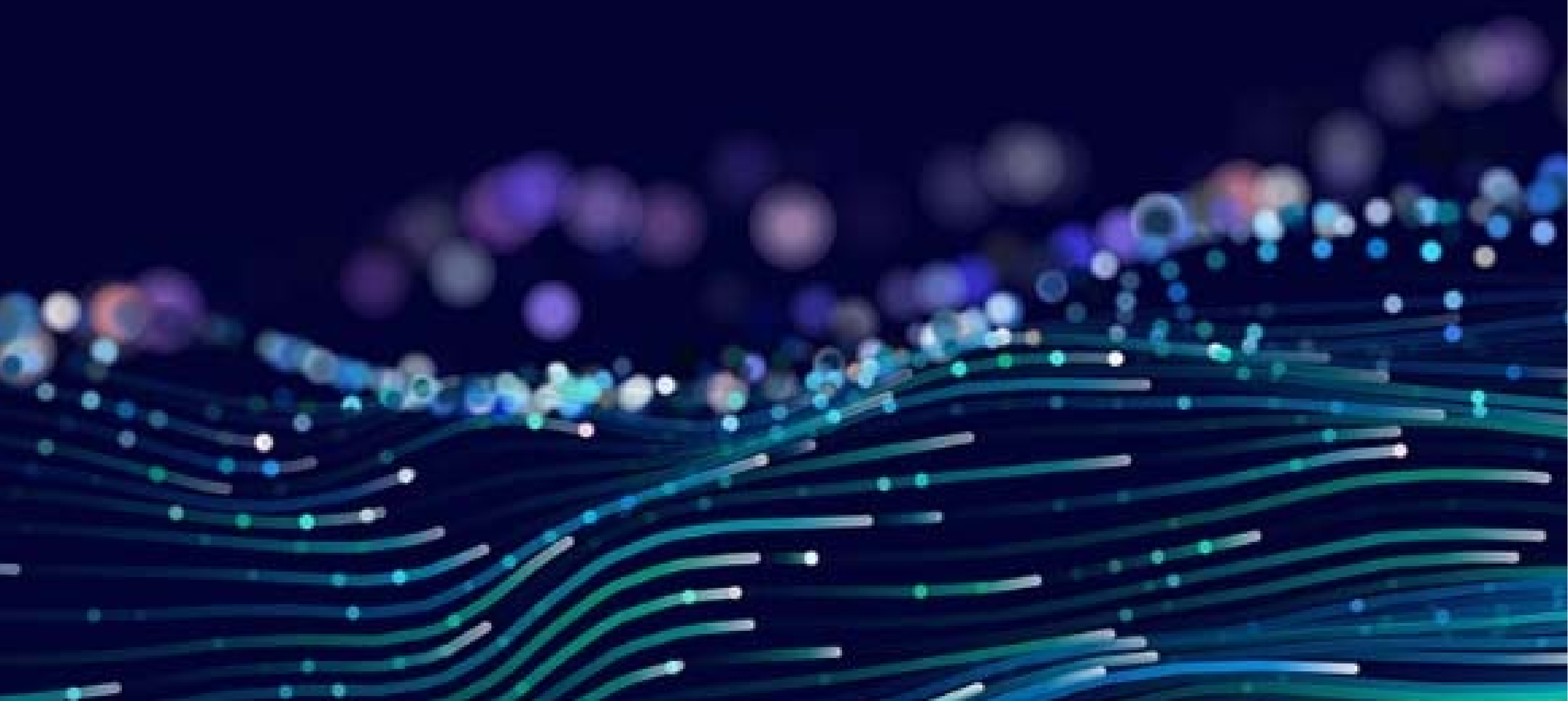
Lasers contribute to global security and forensics. It was possible using laser-based spectroscopy techniques, to non-invasively detect the presence of dinitrotoluene, a material found in many explosives, through layers of nontransparent diffusively-scattering plastics, while proton radiography was shown to be able to detect thin layers of low-Z material behind high-Z shielding.

- *Culture*

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

Thanks to the wide range of non-invasive techniques they are allowing, lasers hold finally an important role in the study and protection of Cultural Heritage artefacts, from ancient coins to medieval gemstones or to invaluable paintings. The unique capabilities of photoacoustic imaging have for instance been exploited – under controlled laboratory conditions – to image preparatory underdrawings while photoluminescence microscopy was used to identify synthetic semiconductor pigments and investigate related degradation phenomena.

NEEDS AND GAPS OF THE EUROPEAN RI COMMUNITY



Supporting transformations and strengthening European competitiveness

To put the scientific potentialities of the laser technologies in practice, a lot of developments and supports are still required. Above all, the three-pillar ecosystem of education, academia and industry needs to be consolidated.

For that purpose, it is first necessary to *reinforce training activities towards not only users but also students from universities and technological institutes* in order to increase the RI human resources.

It is worth mentioning that the access activity of the laser RIs has a strong training component, with a user community mainly university-based and, for instance, more than half of the Laserlab-Europe users below 37 years old. In addition, a global staffing strategy would rely on professional staff development at the European level, involving from continuing vocational training to inter-RI staff exchanges or secondments.

External staffing processes, which appear in the medium to long term vital for the RIs, must of course factor in *gender equality* and *inclusion of minorities*.

Appropriate specialized training in areas with high industrial and societal impact should reinforce the RIs' abilities to innovate. Coupled to a rational expansion of local knowledge sharing and technology transfer policies, it will help turning the innovative concepts developed in the labs into prototypes, paving the way to industrial products, which – at the end – will contribute to maintain the European leadership.

Industrial access to the RIs is also a key component of the European leadership. In fact, a slight majority of the RIs has already opened their facilities to industry or to medical centers, even if not under a standard transnational access activity, showing that industrial access could be functional 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, trans-nationality, or access track delays, should however be addressed to support further industrial access; solutions could encompass a *redefinition of the transnational access requirements* (allowing SMEs accessing local RIs within the laser consortium) *or of the access concept* (allowing not only access to services but also to expertise).

It would be finally valuable to *improve the public awareness* thanks to targeted communication. Social studies indicate that citizens are eager to be correctly informed in order to assess some emerging applications of the laser technologies, such as laser fusion or nanobiomedicine. All these actions shall be mainly conducted at the regional or national level, with – however – an adequate and efficient coordination and some financial incentives at the highest, European level.

Closing gaps and meeting targeted challenges

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The actions described above are nevertheless not sufficient to meet the challenges raised by the foreseen transformations and smoothly closing the gaps between them and the current situation. A *coordinated management of responses to* the European *calls* for proposals aiming at strengthening and improving the role of RIs is thus essential. It is for instance necessary to ensure the continuity of the RI services to users, which includes not only support to transnational user access – and its coordination at the European level - but also common procurement of optics or other laser components (as suggested by the Laserlab-Europe Industrial Advisory Committee) for cost and benefit optimization.

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, e.g., China and has the toolbox necessary to prevent future shortages. Such an action may require to bring relevant industries back to Europe; among the critical components not currently manufactured in Europe, it is worth mentioning beryllium ceramics or selenium-doped crystals. *Implementing material recycling chains* across the RIs would also contribute to minimize tensions on external supply chains.

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

It is possible to already point out the necessity to operate *more energy-effective laser systems and secondary sources*. 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.

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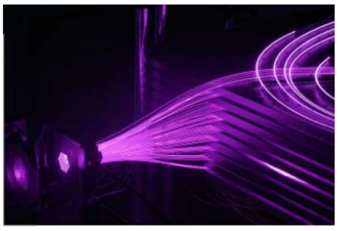
Improvements in terms of efficiency are not only contributing to green the laser technologies but also allowing the development of *portable hand-held laser sources for implantation in clinical environment*. In addition to compactness, in vivo diagnostics require the development of *tunable pulsed laser sources and reliable delivery systems* while entering medical markets involve 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 to communication or remote sensing applications.

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 *standardized 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 optimize laser machining (cutting, welding, additive manufacturing) processes, to predict surgery outcomes or to design laser fusion experiments.



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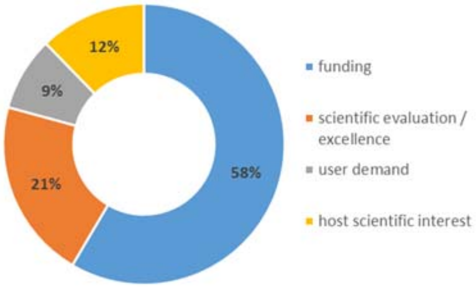
These R&D activities will valuably be supported by the creation of joint research units between companies and RIs, such as HERACLES[3] between Thales, LOA and LULI in France, or at least through RI-industry co-developments.

The need for coordinated access to a variety of instruments or techniques (or to fully-integrated stations clustering laser source, spectroscopy / super-resolution microscopy instruments, optogenetics techniques, models and in-situ data analysis) and for 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 evidenced in the answers to the user survey. Establishing such *multi-instrument access routes across the RI services* could be the first step for a phased approach to clustering. It should be important to mention the large momentum gained towards FELs seeded by laser-accelerated electron beams, which is bridging the gap between FEL and IR laser facilities.

Co-funded access to RIs for research and innovation

Whatever the access route, multi-instrumental as defined above or curiosity-driven, the user community, as a whole, confirms that access to RIs is of upmost importance for conducting an excellent and innovative research. According to the user survey, more than 70% of the users is planning to reapply for access in the future, if support is obtainable.



Such a scenario should be confronted to the RIs' aspirations and capacities. One question of the RI survey was dedicated to identify which is the first motivation to provide access. The answers are reported in the side donut diagram. For more than half of the RIs, the access opportunities are mainly determined by funding availability. Albeit hosting scientifically excellent projects is an important incentive, it is not enough by itself in a realistic picture.

Therefore, if funding is available, RIs are ready to continue supporting transnational access, offering either more services to the users or an increased fraction of beam time, 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 operation costs and, up to a certain degree, national access. However, transnational access – which is at the basis of the excellence of the European research – should continue to benefit from subsidies at the European level, not only to cover user travel & subsistence expenses but also to contribute keeping the RIs from widening countries at the forefront by triggering governmental initiatives.

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

ANNEXES

ANNEX I

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 inscription on ESFRI or national roadmaps (by December 2022) and on 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
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	-	-
	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
	Wigner RCP/Femtolab	member of the Hungarian laser-based RI group	Laserlab-Europe
Italy	CUSBO	reported in the Italian PNRI 2021-2027	Laserlab-Europe
	ENEA/ABC	-	Laserlab-Europe
	FERMI	reported in the Italian PNRI 2021-2027	Laserlab-Europe & LEAPS
	INO/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 Laserlab-Portugal	Laserlab-Europe
	IST/IPFN	Portugese RI as part of Laserlab-Portugal	Laserlab-Europe
Romania	CETAL	-	Laserlab-Europe
	ELI-NP	Romanian RI of European relevance	-
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
	Max IV	Swedish RI project	LEAPS
Switzerland	LACUS	Swiss institution-based station	Laserlab-Europe
	PSI/SwissFEL	Swiss national RI	LEAPS
United Kingdom	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 to 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 ½ and 1 kJ (kJ-scale) or between ½ and 1 PW (PW-scale),
- mid-scale laser facilities: from 100 TW to ½ PW or from 100 J to ½ 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[3] 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[4]).

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 spelled out in annex II.

Very-large-scale RIs

LMJ-PETAL	**LMJ-PETAL is the European highest-energy, MJ-class, Nd:glass laser facility**. Coupling the Laser MégaJoule (LMJ: 300kJ - 80 beams ⬀ *1.3MJ - 176 beams* / 3ns at the 3^{rd} harmonic: 351nm) and the Petawatt Aquitaine Laser (PETAL: 0.9PW ⬀ *1.4PW* / ~10^{19} W/cm^2 / 0.7ps) laser pulses at a rather low repetition rate (1 shot/day), it offers unique capabilities to study, thanks to a variety of plasma diagnostics (currently 18 ⬀ *30*) and to brilliant ultra-short radiation & particle sources, high-energy-density physics for applications in materials science, inertial fusion and laboratory astrophysics. *An external magnetic field generator will allow studying of magnetized plasmas.*

Soon-to-be very-large-scale RIs

AWE/ORION	**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 500J / 1ns laser beams at the 3^{rd} harmonic (351nm) to two laser beams: 1PW ⬀ *3.7PW* / 500fs and 400TW ⬀ *3.6PW* / 500fs ⇩ *150fs*, this latter being at the 2^{nd} 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 CLF.
CALA	The Centre for Advanced Laser Applications (CALA) domiciles two laser sources: ATLAS (CPA Ti:sapphire: 240TW ⬀ *3PW* / 25fs [1Hz]) and PFS-pro (Petawatt Field Synthesizer - Yb:YAG OPCPA: 2.5TW / 40fs / 70-1400nm [10kHz]) 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	The Central Laser Facility (CLF) provides a broadest possible 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 & spectroscopy techniques**.

[3] Laser wavelengths are only mentioned when unconventional; for CPA Ti:sapphire systems, the central wavelength is ~800nm, for Nd:glass systems 1.05µm and for Yb:doped systems 1.03µm.
[4] The ⬀ or ⇩ symbols indicate that the laser parameters preceding them are expected to increase or decrease to the subsequent values in the future.

	GEMINI is a high-power ultra-short pulse CPA Ti:sapphire laser system delivering dual 0.5PW / 30fs [1/20Hz] beams in the TA3 target area or a single 25TW / 20fs [1 Hz] beam in TA2 for investigation of secondary sources generation and applications. *A new facility – EPAC (Extreme Photonics Application Centre) – will be built at the CLF to replace GEMINI; it will comprise initially of a 1PW / 30fs [10Hz] 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' – two target areas: TAW combines dual short laser pulses (2 x 100TW / 1ps) with six long pulses (6 x 80-280J / 0.2-6ns) while TAP is providing up to a 1PW / 0.5ps laser pulse coupled to one of these long beamlines. *The Vulcan20-20 will increase the peak power of the Vulcan laser by 20 times, taking it from 1 to 20PW; it will be achieved by upgrading 6 of the existing long pulse beams from <1.8kJ to ~10kJ and coupling them to one of the existing 100TW beams, to the VOPPEL PW beamline (30J / 30fs @ 880 nm) and to a new very-high-intensity beamline (20PW / 20fs).* ***Vulcan20-20 will thus deliver the highest laser power on possibly 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 & nonlinear IR spectroscopy, TRMPS, FSRS, TAS, 2D-visible SFG, Kerr-gated fluorescence & Raman spectroscopy and time-resolved resonance Raman spectroscopy) thanks to its multiple color, pulse length and repetition rate laser systems serving OPA beamlines. ULTRA A and ULTRA B are CPA Ti:sapphire laser systems delivering respectively 4mJ / 120fs [1 kHz] + 1mJ / 40fs [10kHz] + 1mJ / 2ps [10kHz] and 2mJ / 40fs [10kHz] laser pulses, while LIFEtime is a Yb:doped high-repetition-rate [100kHz] laser system delivering 0.07mJ / 200fs + 0.15mJ / 300fs. ARTEMIS is an ultrafast XUV science facility using 1kHz & **100kHz** (170µJ [1/7µm] + 50µJ [3µm]) 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 100kHz >200W / sub-50fs laser source @ 1µm and additional endstations (e.g. time-resolved MOKE & XUV ptychography).*
ELI-ALPS	The Extreme Light Infrastructure Attosecond Light Pulse Source (ELI-ALPS) has the mission to provide **light sources of the shortest possible light 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-fiber High Repetition (HR) laser system provides, at 1030nm, 1.8mJ / 30fs [100kHz] laser pulses, post-compressed down to 1mJ / 6.5fs (*⬀ 5mJ / <6fs with CEP stabilization*) to drive secondary harmonics (gas & condensed targets) sources serving TAS, ReMi (COLTRIMS), NanoESCA (LEED, XPS, PEEM, AES, RGA, momentum microscopy, ARPES, 2D spin analyzer) and VMI endstations. A dedicated chamber for sample preparation is available to users. *An auxiliary (alignment) laser source (1mJ / 7fs [1kHz]) will soon be operational.* - The OPCPA Mid-Infrared laser system (MIR) delivers 100kHz 130µJ / 42fs pulses centered at 3.15 µm, post-compressed down to 70µJ / <20fs. 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 >20mJ / <50fs, post-compressed to 10mJ / <25fs, delivered at 1kHz in the 2600-3600nm wavelength range or >12mJ / <100fs in the 1400-1700nm range.* - The single-cycle NOPA laser SYLOS produces post-compressed 3.4TW *⬀15TW* / <8fs pulses around 891nm and is complemented by the so-called SYLOS Experimental Alignment (SEA: 10mJ *⬀15mJ* / <4.5fs), operated at a lower repetition rate [10Hz]. 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 (>400TW *⬀2PW* / 22-27fs *⬂17fs* [10Hz]) *and HF-100 (50TW / 10fs [100Hz]). HF will mainly be used to drive secondary harmonics (solid) and electron sources.* - The Nonlinear Terahertz Spectroscopy Facility (NLTSF) consists of 6mJ / 220fs [1kHz] + 1TW / 500fs [50Hz] Yb:CaF2 pump lasers at 1030nm and of a THz / optical pump - THz probe system (coupled to optical spectroscopy and electro-optic THz detection setups); THz pulses with more than 200kV/cm peak electric field are available on sample. *The High-Energy Terahertz Beamline (HE-THz) will allow reaching more than 1mJ of THz energy.*

ELI-Beamlines	The Extreme Light Infrastructure Beamlines (ELI-Beamlines) will offer to users **ultra-high-power (up to 10 PW) laser pulses with high repetition rates** – allowing reaching ultra-high focused intensities up to 10^{24} W/cm^2 – 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 3.6TW ⬀ *6.5TW* / 15fs / 750-920nm pulses at <1kHz *(soon to be synchronized to a second >10mJ beam)*. It drives secondary harmonics (gas) & plasma x-ray (PXS) sources for multidisciplinary physics experiments using four endstations: MAC (electron- & ion-ToF, VMI, MBES, CDI), TREX (XRD, XRS, XAS, XES *& 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 120TW / 25fs pulses at 820nm and at >20Hz high repetition rate, passively synchronized to a 5mJ / 30fs / 2.2µm [2kHz] 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 500TW ⬀ *1PW* / <28fs pulses at 800 nm at a repetition rate of <3⅓Hz ⬀ *10Hz for plasma physics experiments and to drive electron, x-ray (Compton and betatron) and ion secondary sources. The ELBA electron beamline will allow achieving the highest energy and high quality electron beams while the ELIMAIA ion beamline will be used, among 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 - 600J ⬀ *1.2kJ* / 2-3-10ns ⬀ *0.5-10 ns* @ 1.053µm [1 shot/2min ⬀ *1 shot/min] - coupled to a short PW-class beam - 1PW / 150fs / 1.060µm beam [1 shot/min] - or 2/ one single extremely high peak 10PW / 150fs / 1.060µm beam [1 shot/min]* for laser-matter interaction research *or particle acceleration.*
ELI-NP	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 820nm with 2 x 100TW / 22fs [10Hz], 2 x 1PW / 25fs [1Hz] *or 2 x 10PW / 23fs [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 coupled to a γ–ray beam*** *(with tunable photon energy up to 19.5MeV and spectral density above 1000 ph/s/eV).*
LULI	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 & radiation source generation and applications, and to high field physics, thanks to, currently, 1PW / 20fs 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 ⬂ 15fs), F4 (100mJ / 20fs) and F3 (delivering the remaining energy, up to a total of 250J, 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 800J / 1.5-15ns beams (one of them possibly compressed down to 100J / 1ps), one auxiliary probe beam 50J / 1.5-15ns, and 2 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 ~40T. HERA is dedicated to laser shock generation and material study (LIDT, shock peening and adhesion & mechanical testing); the Nd:glass laser system delivers, every 20 minutes, 200J / 5-15ns pulses. *A second beam, with the same parameters, will soon be operational.*

These RIs should be completed and fully operational in the coming years. The European leading position will thus be reinforced with six very-large-scale laser RIs representing more than 1 MJ of energy and roughly 60PW of power.

Large-scale RIs

CETAL	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 at exploring laser-matter interaction at ultra-high intensities, focusing on applications – mainly through radiation & particle secondary sources – thanks to two CPA Ti:sapphire laser systems: CETAL-PW (1PW / 25fs [0.1Hz]) and TEWALAS (15TW / 25fs [10Hz]). 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 nanometer 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 allow increasing the availability of the primary & secondary sources while new fiber-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	The Centro de Láseres Pusados (CLPU) is the key Spanish RI specialized in high-intensity ultrashort lasers. The architecture of the Ti:sapphire laser system VEGA allows offering to users access to three independent and synchronized beamlines: VEGA-1 (20TW / 30fs [10Hz]), VEGA-2 (200TW / 30fs [10Hz]) and VEGA-3 (1PW / 30fs [1Hz]), 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, making 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 10Hz J-level ns sources) will soon be added to the VEGA facility for pump-probe experiments and synchronization 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	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 <280TW / 0.5ps pulses every 90'. One low-power (<10TW) and one full-power stand-alone target areas are available to users for laser-plasma interaction experiments and for generation & applications of secondary sources. A programmable nanosecond front-end allows for <1kJ pulses with a deterministic pulse profile within a 0.5-10ns 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 200ps) is made possible, but at limited energy (<30J each). A third target area (Z6) allows for combined laser / UNILAC <13MeV ion beam experiments; PHELIX is then coupled to the nhelix beamline (100J in the ns regime or 20TW / 500ps) 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 <1GeV ion beam experiments will soon be open to users.*
HZDR/ELBE	In addition to a superconducting electron accelerator and to its secondary radiation sources, ELBE at the Helmholtz Zentrum Dresden-Rossendorf (HZDR) consists in two high-power laser systems. The first CPA Ti:sapphire laser system, DRACO is delivering, at 1Hz, two laser pulses (670TW & 150TW / 30fs) 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 e.g. for 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 1PW / 150fs / 940nm [1Hz] 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	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 1315nm 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 600J and an auxiliary one at 100J. Both beams are precisely synchronized with a CPA Ti:sapphire laser beam (22TW / 45fs [10Hz]) 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	CELIA (Centre Lasers Intenses et Applications) proposes three reliable lasers systems, including a **unique MHz Yb:fiber laser source**, secondary (harmonics, betatron) radiation sources and nine fully equipped endstations (XANES, LIBS, VMI, COLTRIMS, FDI, polarimetry, shadowgraphy, Raman spectroscopy) dedicated to a number of specific applications. - AURORE (Ti:sapphire: 2x7mJ / 25fs / 800nm, post-compressed down to 10mJ / 10fs [1kHz]) - ECLIPSE (Ti:sapphire: 5TW / 30fs (post-compressed down to 1TW / 10fs) [10Hz] or 2x30TW / 30fs [1Hz]) - BLASTBEAT (Yb:fiber: 2x50W / 130 fs / 1030nm [0.166-2 MHz]) *AURORE will be upgraded towards improved stability and higher peak power, but lower repetition rate (>100TW / 30fs [1Hz]). A new radioprotected experimental area will be open on ECLIPSE and a new ARPES endstation on BLASTBEAT. A new >10GHz Yb:fiber laser source will also be developed and connected to a micromachining bench.*
ENEA/ABC	The ABC facility operated at the ENEA Frascati Research Centre is made of a **two-counterpropagating-beam Nd:glass laser system** (2 x 100J / 2.5-7ns [1 shot per 20 minutes]), completed with a 4-beam probe laser system (4x100mJ / 0.5ns / 0.53µm), and a well-equipped experimental area for fusion-related and EMP studies.
HIJ	The Few-Cycle-Laser laboratory at the Helmholtz Institute Jena (HIJ) is operating various laser sources for the investigation of strong field and attosecond laser physics as well as for 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 (200TW / 100fs / 1030nm [1/50Hz]) while JETI200 is a Ti:sapphire laser system delivering 200TW / 20fs / 800nm [5Hz]; additional kHz mJ-class few-cycle laser sources are also available and **on-shot CEP phase metrology** 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 10m implemented.*
HiLASE	HiLASE provides a **unique platform for industrial partners** by operating two diode-pumped solid-state (Yb:YAG) kW laser facilities. BIVOJ delivers 100J / 10ns / 10Hz laser pulses, while PERLA generates 13mJ / <1.5ps / 1 kHz pulses at the fundamental wavelength (PERLA B) or, at lower energy but higher repetition rate (50 or 100kHz), 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 characterization 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 500Hz. 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).*
INO/ILIL	The Intense Laser Irradiation Laboratory (ILIL) at the Pisa research unit of the National Institute of Optics (INO) operated a CPA Ti:sapphire laser chain and two interaction areas; the first one, served by the pre-compressed frontend output light (10TW / 40fs [10Hz]), houses two target chambers (with focal lengths of up to f/15 for laser-driven electron acceleration and of f/4.5 for laser-solid interaction); the second one, radiation shielded, allows multi-purpose experiments at full power (240TW / 25fs [2Hz]). *It is foreseen to add to the facility additional CPA Ti:sapphire (<1J [100Hz] / 30fs and 20mJ [1kHz] / 30fs) and mid-IR (1.5 mJ / <70fs [1kHz]) laser sources. In the framework of the Italian Tuscany Health Ecosystem (THE) project, a very high dose rate radiotherapy source will be realized.*
LIDYL	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 - 100TW or 2x50TW / 25fs /10Hz) 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 stabilized FAB1-10 laser (15mJ / 25fs / 1 kHz or 2mJ / 25fs / 10 kHz) with 2 harmonic beamlines providing **VUV-XUV fs/as pulses** (up to 100nJ @ 1kHz or 10nJ a@ 10kHz) **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 –300µJ / 50fs @ 1µm, 15µJ / 38fs @ 1.8µm, 13µJ/ 65fs @2.4µm [100kHz]); XUV harmonic beamlines (up to 60eV from gases or up to 26eV from crystals) are also available; - FLUME, a **rare FLUPS set-up in the visible and UV regions (down to 267nm) with 100fs resolution** to study time-resolved emission spectra of molecules in the condensed phase. *An upgrade of the ATTOLAB facility (to reach the 100kHz repetition rate) is foreseen.*
LOA	LOA (Laboratoire d'Optique Appliquée) provides unique instrumentations in the field of ultrafast laser-plasmas with laser duration down to an optical cycle & **high repetition-rate, multi-beams synchronized at the fs timescale**, and fixed experimental setups: - Jaune (Ti-sapphire: 10Hz / 2x60TW / 30fs coupled to 0.5J / 500ps and, possibly, 6 low-energy laser beams) serving 4 beamlines for studies of electron acceleration (and related applications, such as x-ray induced – Compton, betatron – sources) and XRL (1µJ / 300fs / 30nm); - Noir (post-compressed Ti:sapphire: 1TW / 3.5fs / 1 kHz) for electron / proton acceleration and XUV harmonic emission from solids; - Violette (Ti:sapphire : 15mJ / 50fs [100Hz]) for lasing in gas, THz and acoustic generation and (Ti:sapphire: 6TW / 50fs [10Hz]) for filamentation and laser-induced breakdown; - Corail/Argent (Ti:sapphire OPCPA: 3mJ / 40fs / 5kHz coupled to <1mJ / 30fs / 1 kHz) serving 5 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 (1J / 25fs / 100Hz) will be commissioned in the future. The related LAPLACE project, allowing also the construction of a new beamline devoted to high-dose radiobiology using electrons and photons, will reinforce the Greater Paris leadership in laser-plasma acceleration.*
LFN/SPARC_LAB	The SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Laser And Beam) facility at the National Laboratory of Frascati (LFN) consists in 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 (200TW / 25fs plus <2TW / 30fs [10Hz ⇗ *100Hz*]). FLAME is employed to study laser-matter interaction, including LWFA electron acceleration and betatron radiation or TNSA ion generation. An external injection beamline allows studying **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 1GeV X-band RF linac and to upgrade FLAME up to the 0.5PW range.*
STRATH/SCAPA	The Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) at the University of Strathclyde hosts three CPA Ti:sapphire laser systems (350TW / 25fs [5Hz] – 13mJ / 25fs [1kHz] – 40TW ⇗ *100TW* / 35fs [10Hz]) 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 at providing state-of-the-art characterization 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	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 (100-850mJ / 5ns / frequency convertible up to the 4th harmonic [1-20Hz]) for laser processing and a Ti:sapphire one (7 mJ / <100fs / 290 - 2600 nm [1kHz]) 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 200kHz), covering a large range of wavelengths, as well as an ultra-stable optical (450-2000 nm) frequency comb synthesizer and a magneto-optical trap for Ru atoms. A variety of spectroscopy / microscopy / imaging techniques will be available, among which the most innovative are time-resolved ARPES, nano-FTIR, SNOM, CRDS, LIBS and ICP-OES.*
CLL	The Coimbra Laser Lab (CLL) is specialized on 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…). For that, 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 (100nm) fluorescence imaging and a high-repetition-rate mJ laser source will be soon commissioned.*

CLUR	The Ultrafast Lasers Center (CLUR) at the Universidad Complutense Madrid is specialized 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 / <1J / 202-1064nm [10Hz] laser systems, as well as the Ti:sapphire FEMTO1 (3.5mJ / 35fs / OPA 235nm – 3µm) and FEMTO2 (1mJ / 80fs) 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 / 1kHz / 5fs) serving a XUV attosecond beamline is under construction.*
CUSBO	Several unique state-of-the-art sources provide at CUSBO (Center for Ultrafast Science and Biomedical Optics) few-cycle light pulses, either widely-tunable or of high peak power. - STRATUS (Ti:sapphire OPA: 100fs / 1 mJ @ 800nm / 500-2000nm [1kHz]) - post-compressed Ti:sapphire SERAPIDE (1mJ / 4fs [10kHz]), ELYCHE (2.5mJ / 4fs [1kHz]) and FEXRAYS (0.8mJ / 5fs [1kHz]) - ULTRAS-TW (Ti:sapphire OPA : 1.5mJ / 20fs / 1200-1900nm [10Hz]) These sources are used to seed isolated attosecond and XUV (14-55eV / 15fs) harmonic beamlines for pump-probe experiments. Additional tunable visible (430-480 & 500-700nm) and near-IR (900-1500nm) NOPA sub-30fs 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, e.g., non-invasive clinical diagnostics & 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, among which: multifunctional time-domain diffuse optical tomography, multiscale high-resolution, or the use of quantum light for ultrafast spectroscopy and imaging.*
DESY/CFEL-ATTO	The Femtosecond and Attosecond Laser Spectroscopy group at the Center for Free-Electron Laser Science (CFEL-ATTO), located on the DESY's Hamburg campus, is offering access, in addition to the FLASH free electron laser, to a series of beamlines: - XUV (15-50eV) attosecond (200as) nJ-level pulses combined with sub-2fs UV (210-340nm) and sub-4fs NIR (450-1000nm) pulses for **3-color ultra-fast covariance detection** (electron/ion VMI, ion mass spectrometer, molecular beams and liquid jet available), - an IR synthetizer driving an attosecond soft x-ray (280-530eV) beamline, - two home-made laser systems for high-energy applications (1J / 300ps / 1.03µm [300Hz] and 100mJ / 900fs / 1.02 µm [1kHz]), - a high-average-power IR frequency comb (80W / 200fs post-compressed to 40fs /1.03µm [65MHz]) fully stabilized.
HEPHAESTUS	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 240nm to 2.6µm) at the sub-10mJ energy level, to ns-class >Hz laser sources and to secondary harmonic sources. A variety of techniques and instruments is 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 (2.4-0µm) fs one for mid-IR TAS or table-top x-ray lasers, currently under construction.*
ICFO	ICFO (Institut de Ciències Fotòniques) aims at advancing laser science, focusing notably on **few-cycle CEP-stabilized 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 (1.1-2.4µm) post-compressed OPCPA system (<2mJ / <12fs @ 1.8µm [4kHz]), a Nd:YV04 post-compressed OPCPA system (16µJ / 15fs / 3.2µm [160kHz]) and a Ho:YLF OPCPA system (0.7mJ / 188fs / 7 µm [100Hz]). 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. *An upgrade of the attosecond soft x-ray beamline, towards higher flux, and of the spectroscopy instruments, towards higher resolution (1/3000 at the O edge), is planned.*
IEP-TU Graz/NanoESCA	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	LASERIX at the Laboratoire de physique des deux infinis Irène Joliot-Curie (IJCLAB) is a 40 TW laser facility comprising three 40fs / 10Hz distinct beamlines (40TW, 30mJ 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	The ZEUS Ti:sapphire laser facility (45TW / 23fs [10Hz]) at the Institute of Plasma Physics and Lasers (IPPL) 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 (1-10keV, 226124nm and acoustic) and particle (50-100MeV electrons, 1-2MeV protons) sources. Auxiliary lasers (including a 7fs / 2mJ [1kHz] CEP-stabilized Ti:sapphire source and Nd:YAG sources in the ns (800mJ) and ps regime (250mJ) at 10Hz) are also available for material science or laser fusion basic physics. *New laser sources (Nd:YAG 1J & fiber cw 2000W @ 1.08µm) are expected in the near future.*
ILM/X-2M	X-2M at the Institut Lumière-Matière (ILM) of the University of Lyon provides several beamlines devoted to the irradiation of atomic/molecular, solid or liquid targets by intense light pulses, over a broad spectral domain, from 2-40THz and IR to extreme UV (10-100eV), and with durations from picoseconds to few hundreds of attoseconds, driven by a post-compressed CEP-stabilized Ti:sapphire laser source (1mJ / 7fs [5 kHz]). Techniques such as VMI, electron and ion TOF, TAS, LCMS or IRMPD are available to users. *A new end station devoted to soft x-ray TAS will be soon commissioned.*
IPHT/LPI	*The Leibniz Center for Photonics in Infection Research (LPI) will help to revolutionize 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	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	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 (65µJ ⇗ *1mJ* / 40fs / 3.2µm [100kHz]) and L2 NIR (1mJ / 1ps / 1.03µm [100kHz]). 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 – 5mJ / 35fs [1kHz] or 25mJ / 40fs [10Hz]). *Post-compression will be soon implemented to reach sub-fs duration.*
LACUS	The Lausanne Centre for Ultrafast Science (LACUS) offers various instruments for the investigation of matter (molecules, solutions, proteins, solids and nanosystems) in out-of-equilibrium conditions. It operates two facilities: - HARMONIUM, a high-order harmonic source (served by a 15W [6kHz] NIR source) providing VUV (15-100eV) fs pulses to 3 beamlines for steady-state and time-resolved ARPES, photo-electron spectroscopy and XUV absorption of liquid micro-jets, complemented by the YPERION XUV source (9-11 eV [1MHz]) - LOUVRE, a 20kHz laser source providing tunable (260-380nm) and continuum (520-760nm and 260-280nm) deep-UV pulses for TAS and circular dichroism studies as well as FLUPS, UED and TEM setups. *This latter will be replaced this year.*
Laserlab DK	Laserlab DK is an interdisciplinary Danish network aimed to strengthen 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	The Laser Laboratory of the Nanoscience Center (Laserlab-NSC) is a shared facility housed on the NSC. It combines laser spectroscopy with nanoscience thanks to three fs laser systems and with more than ten other spectroscopic setups enabling various experiments in time- and frequency domains and also imaging. Laserlab-NSC is focusing on vibrational spectroscopy (IR and Raman), nonlinear spectroscopy and imaging, biomolecular spectroscopy, plasmonics, and development of analytical methods. *Access to a SNOM facility is available.*
LENS	LENS, the European Laboratory for Non-Linear Spectroscopy, is a center 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	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, strong focus is 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 TeraWatt (Ti:sapphire NOPA – 2x2.5mJ / 7.6fs / 720-1040nm [30Hz]), as well as secondary harmonic sources and complementary setups (frequency combs, multi-trap optical tweezers). Multiple end stations 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 not only in the near-IR range but also in the visible.*
LLC	The laser sources operated by the Lund Laser Center (LLC) include, among others, two CEP-stabilized laser sources - Attolab (Ti:sapphire OPA - 5mJ / 20fs / 770-830nm [3kHz]) and, especially, a 200kHz few-cycle Yb:rod NOPA (MHz: 15µJ / 6fs / 850nm) - and a terawatt Ti:sapphire dual-beam facility (40TW / 35fs coupled to 100mJ in the ns regime [10Hz]). Several laboratories are served, for quantum optics (using cw single-mode laser source and cryostats), femtochemistry (with, e.g., a sub-ps THz spectroscopy set-up), combustion (which allows diagnosing matter in harsh environment) or biomedicine (fluorescence diagnostics). Additionally, CARS, LIDAR or fs LIF setups are available. *The terawatt laser source will be very soon replaced by a dual 50mJ / [100Hz] + 250mJ [10Hz] / <10fs OPCPA T^3 laser and a short-wave IR OPCPA system (13µJ / 15fs / 1.8µm [200kHz]) will be made available.*
LP3	ASUR is the major laser source operated at the laboratoire Lasers, Plasmas et Procédés Photoniques (LP3: Ti:sapphire – 20TW / 25fs [10Hz] or 10TW / 25fs [100Hz]); it allows driving a pulsed hard (17.5 & 8.05keV) x-ray source at a repetition rate of 100Hz 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 functionalization 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	The Max-Born-Institut (MBI) conducts basic research in nonlinear optics, ultrafast dynamics, laser-matter interaction, and into the resulting applications, thanks to a series of ultrashort and ultrafast lasers over a wide laser spectral range, from 800nm to 5µm: - a Ti-sapphire OPCPA laser source (190µJ / 7fs [100kHz]), - a post-compressed Yb:YAG OPA laser source (>3TW / 9fs / 1030nm [100Hz]), - a IR / mid-IR dual-beam 100kHz Yb:YAG OPCPA system (430µJ / 51fs / 1.55µm + 125µJ / 73fs / 3.1µm), - a multi-MW Ho:YLF OPCPA laser source (3.1mJ / 80fs / 5µm [1kHz]). 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	Research being undertaken at the Laboratory for Attosecond Physics of the Max-Planck-Institute for Quantum Optics (MPQ) aims at developing basic tools for real-time observation of, and control over, electronic motion on an atomic scale; the group relies mainly upon CEP-stabilized ultra-short laser sources, either Ti:sapphire ones or in the mid-IR wavelength range and at the multi-mJ energy level (HORUS and ACCORD), serving attosecond XUV beamlines. *If the first systems will be decommissioned in the near future, the second ones will be upgraded to higher repetition rates or energy outputs (depending on the systems).*
MULTI-NANO	The Hofkens lab (MULTI-NANO) applies – on a wide variety of timely and societal relevant topics – a set of different instruments: super-resolution imaging, ultrafast spectroscopy, scanning probe microscopy, correlated imaging, etc.
MUT-IOE	The Institute of Optoelectronics at the Military University of Technology (MUT-IOE) is a leading research institution on laser development and application in Poland. The specific areas of research activities 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 1-10ns / <10J laser irradiation of a gas puff target at 10Hz. 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	The Spin Polarized Research Instrument in the Nanoscale and Time (SPRINT) at the Nanoscience Foundries & Fine Analysis in Trieste (NFFA-Trieste) offers to users two workstations: - a high-order harmonic beamline (17-31eV / 100fs [200kHz]) coupled to OPA pumps (210nm-1.6µm / 200fs and 630nm-2.5µm / 30-50fs), a vectorial Mott detector and a high-resolution (22meV) hemispheric electron analyzer (suited for 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 / <300fs laser pulses at 1.03µm and 515nm [50kHz-1Mhz]) 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	TARANIS, a Nd:glass facility, at the School of Mathematics and Physics of the Queen's University of Belfast (QUB) delivers two optically-synchronized pulses at a repetition rate of 1 shot per minute: 20TW ⬀ *60TW* / 0.5ps and/or 30J ⬀ *80J* in the ns regime. The facility is equipped with two target areas, the first one being dedicated to high-intensity laser-matter interaction – and to the development and applications of secondary sources – and the second one to the study of high-energy ns laser-matter interaction. *A kHz, fs, mJ source is currently being developed to complement the facility.*
SMARTLIGHT	*SMARTLIGHT will become – in roughly 5 years – 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	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 – 2.5mJ / 25fs [1kHz]) allows studying 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 stabilization module will be soon in operation.*
SCSTI/ILC	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 utilizing advanced laser sources is foreseen.*
ULF-FORTH	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 17.5TW / 20fs [10Hz] or 3mJ / 25fs [1kHz] one, - a Nd:YAG-dye laser source (2mJ / 10ns / 400nm -4µm [10Hz]), - a KrF laser source (10mJ / 150fs-450fs-5ps [1-10Hz]), - as well as additional tunable visible-UV-VUV low-energy laser sources (220-1800nm / 5-20ns), *soon to be replaced by a dye-OPA NIR system tunable from 400nm to 4µm*. These laser sources allow the generation of secondary sources, from tunable XUV (55-115nm) high-flux (10^{5-11} ν/pulse) photon sources to UV-NIR and 0.11-10THz radiation sources. Workstations for micro/nano-processing, material characterization (XRD, TEM, SEM, etc.) and biophotonics (integrating live cell microscopy, non-linear imaging, cellular manipulation and bioprinting) are accessible, as well as a series of techniques (SHIM, MPM, fluorescence molecular tomography, slice imaging, photoacoustic imaging, TAS).
ULLC	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, and chemical physics, astrophysics, as well as applications of laser techniques, such as FLIM, OCT, Raman spectroscopy and B-field imaging microscopy or magnetometry using diamond NV centers.
USZ/HILL	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 (100mJ / 600fs coupled to 60mJ / 150fs [10Hz]) 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 (thanks to multiplexing) are foreseen as well as commissioning of a new ArF laser source at 193nm.*
VULRC	Vilnius University Laser Research Center (VULRC), where the first proof-of-concept experiment on OPCPA was conducted in the 90's, 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 (0.1mJ / <300fs / 1350-2900nm [200kHz]), Ti:sapphire OPA (50µJ / 50-100fs / **computer-assisted tunability from 240nm to 13µm** [1kHz]), Yb OPA (0.4mJ / 210fs [1kHz-1MHz]), Nd:YAG (<30W / sub-ns & ns [Hz-kHz]) and Ti:sapphire (<10mJ [kHz]). The list of laser-based techniques offered is impressive, for advanced spectroscopy and imaging, nonlinear optics, material processing, light-matter interaction at direct laser writing 3D lithographic fabrication conditions and microfluidics.
Wigner RCP/FemtoLab	The Ultrafast Nanooptics Research Group (FemtoLab) at the Wigner Research Centre for Physics operate a series of Ti:sapphire oscillators OPAs – among them: 7mJ / 35fs [1kHz], 0.4mJ / 35fs [10kHz], 260nJ / 60fs [3.6MHz] and 2.5nJ / 5fs [80MHz] – and harmonic radiation sources for, e.g., studies of ultrafast phenomena in condensed systems and nanostructures, nano-optics and plasmonics, using e.g. TOF setups, hemispheric spectroscopy or retarding potential electron spectroscopy.

Free-electron laser RIs

CLIO	The Centre Laser Infrarouge d'Orsay (CLIO) is a platform operating a pulsed free-electron laser continuously tunable between 2.5 and 150µm and delivering pulses of duration adjustable from 5 to 10ps at 62MHz. It can lase simultaneously at two different, independently tunable, frequencies, allowing 2-color 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 266nm, coupled to ion traps – or in the IR range thanks to OPOs operating in the 2.5-5µm range in the ns regime). *Thanks to a 2022 grant of the Paris-Saclay University, replacement of the klystron is scheduled.*
European XFEL	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 <25fs-long x-ray flashes (27000 pulses/s) are distributed to three beamlines – SASE1 and SASE2 (0.05-0.4nm), SASE3 (0.4-4.7nm) – 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 generating matter under extreme conditions of pressure, temperature or electric field using the FEL radiation, *pulsed magnets* and the HiBEF laser sources: the 5Hz CPA Ti:sapphire laser source ReLAX 3J / 25fs *and soon the 10Hz Yb:YAG laser source Dipole 100-X 100J / 2-10ns*. - SQS for investigations of fundamental processes of light-matter interaction in the gas phase (electron- & 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 polarization and attosecond duration) as well as additional beamlines (SASE4 and SASE5) – serving 4 new instruments – and implementation of superconducting undulators to allow delivering harder photons (from 30 to 80 keV).*
FELIX	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 polarized 0.3-5ps pulses at 1000MHz. - FEL-1: 20-150µm - FEL-2: 2.7-45µm - FELICE: 3-100µm - FLARE: 100-1500µm 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 & 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	Unique among 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 polarization and a peak brightness ten billion times higher than that made available by third-generation light sources – delivered by two beamlines: FEL-1: 20-100nm (50-100fs) and FEL-2: 4-20nm (20-60fs), at 10-50Hz. FERMI is opening opportunities for exploring 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- & ion-TOF, MBES, VMI and CDI techniques are also available, as well as a CPA Ti:sapphire laser (<1mJ / 80-250fs) for pump-probe experiments. *An upgrade aiming 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, is planned on FERMI (FERMI2.0). New features will also include laser & FEL light pulses with orbital angular momentum.*
DESY/FLASH	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 4.2-51nm pulses with duration <30-200fs while FLASH2 delivers 4-90nm pulses with duration <10-200fs, both at 5kHz. In addition, it is possible to produce THz pulses (10-230µm) fully synchronized with the FLASH1 soft x-ray pulses. Additional laser sources (Ti:sapphire: 10mJ / 60fs [10Hz] and Yb:doped: 20µJ / 100fs [10kHz]) for FLASH1, OPCPA: 200µJ / <100fs / 700-900nm [1kHz] for FLASH2) are available to users as well as techniques such as VMI, COLTRIMS, electron- & 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 characterization 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	Operated by HZDR, the free-electron-laser facility FELBE relies on the superconducting linear accelerator ELBE, operating in cw mode with a 13MHz repetition rate, to serve two FEL beamlines – U37 (5-40µm / 1-10ps) and U100 (18-250µm / 3-30ps) – and several user laboratories. Techniques such as optical sideband generation, time-resolved photoluminescence, magnetospectroscopy, IRS, SNOM, s-SNIM *and soon ARPES*, as well as additional synchronized 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 (10-500kHz) THz facility, which delivers low-frequency, CEP-stable 150-3000µm / 5-100ps pulses for probing ultrafast terahertz-induced dynamics in various states of matter with highest precision.
MaxIV/SXL	*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 3GeV linear accelerator.*
PSI/SwissFEL	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 (0.1-0.7nm) operated in SASE or self-seeded modes and delivering single, linearly polarized, 13fs pulses at 100Hz, - ATHOS in the soft x-ray range (0.65-5nm) operated in a SASE mode and delivering single 11fs pulses at 100Hz with variable polarization, currently serving three experimental stations, the first 2 on ARAMIS, the 3rd 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: atomic, molecular and non-linear X-ray physics and chemical dynamics (COLTRIMS, TAS, XRD, hemispherical electron analyzer, ion-TOF). Additional optical Ti:sapphire laser sources (OPA & 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, will aim at implementing 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	*The Polish free electron laser (POLFEL) will provide tunable coherent electromagnetic radiation in the range from 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	*The Southern Europe Thomson Back-Scattering Source for Applied Research (STAR) aims at offering advanced scientific investigation services in the field of fundamental and applied research on materials. It will be equipped with a powerful new concept of 30-85keV, 100Hz x-ray source (based on Thomson backscattering) equipped with an experimental microtomography station which allows to examine, through the acquisition of 3D images at very high resolution, 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.*

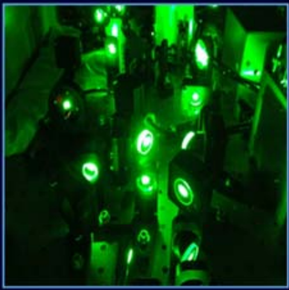
Annex II

Glossary

AAS	atomic absorption spectroscopy
AES	atomic emission spectroscopy
AFM	atomic force microscopy
AFMIR	atomic force microscope-infrared spectroscopy
AOSLO	adaptive optics scanning laser ophtalmoscopy
ARPES	angle-resolved photo-emission spectroscopy
CARS	coherent ant-Stokes Raman scattering
CDI	coherent diffractive imaging
CEP	carrier-envelope phase
COLTRIMS	cold target recoil-ion momentum spectroscopy
CPA	chirped pulsed amplification
CRDS	cavity ring down spectroscopy
DAC	diamond anvil cell
EBS	enhanced backscattering spectroscopy
EDX	energy-dispersive x-ray spectroscopy
EPR	electron paramagnetic resonance spectroscopy
EXAFS	extended x-ray absorption fine structure
FCS	fluorescence correlation spectroscopy
FDI	Fourier-domain interferometry
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 fluorescence 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 localization microscopy
PEEM	photo-emission electron microscopy
PCI	phase contrast imaging
PLD	pulsed laser deposition
ps	picosecond (10-12 s)
REMPI	resonance-enhanced multiphoton ionization spectroscopy
REXS	resonant inelastic scattering
RGA	residual gas analyzer
RICS	raster image correlation spectroscopy
RIXS	serial femtosecond crystallography
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 florescence 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
XMCD	x-ray magnetic circular dichroism
XPCS	x-ray photon correlation spectroscopy
XPES	x-ray photoelectron spectroscopy
XPS	x-ray photoelectron spectroscopy
XRL	x-ray laser
XRS	x-ray Raman scattering
XRD	x-ray diffraction



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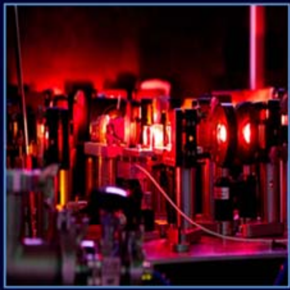

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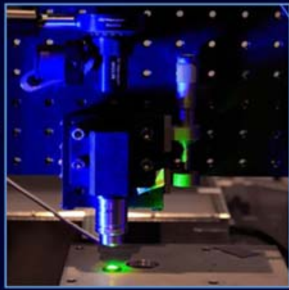

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