PROJECT FINAL REPORT

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1. Final publishable summary report

1.1 Executive summary

Laserlab-Europe is a European consortium of major laser Research Infrastructures (RIs), forming an Integrated Infrastructure Initiative (I3). Geographically, Laserlab-Europe covers the majority of European member states, and scientifically it covers most areas of laser science and applications, with particular emphasis on short pulses and high intensities. Novel applications range from coherent x-ray generation, laser particle acceleration, laboratory astrophysics, and attosecond physics to fusion research, materials research, and biomedicine, to name a few.

The main objectives are:

- To maintain a competitive, inter-disciplinary network of European national laser laboratories;
- To strengthen the European leading role in laser research through Joint Research Activities, pushing the laser concept into new directions and opening up new applications of key importance in research and innovation;
- To offer Transnational Access in a highly co-ordinated fashion for the benefit of the European research community;
- To increase the European basis in laser research and applications by reaching out to neighbouring scientific communities and assisting in the development of laser research infrastructures on both the national and the European level, particularly the Pan-European infrastructure ELI.

Networking, Joint Research Activities (JRA) and Transnational Access (TNA) play hand in hand towards the overarching objective of structuring the European landscape of laser RIs and their operation, with the balance between competition and cooperation being one of the most important structuring elements. For example, Laserlab-Europe's "Dynamic Access" policy forces the host infrastructures towards uniqueness at the European level, introducing elements of competition among them. On the other hand, they strongly cooperate within the JRAs towards overall improvement of access opportunities at the European level. Finally, a well-established but dynamically developing set of networking activities, including the "virtual infrastructure development", user relations and training, scientific and technological exchanges, foresight activities and international relations complement the inventory of RI structuring tools.

The present report addresses activities during the contract and funding period from June 2012 until November 2015. Laserlab-Europe's TNA programme involved, during this period, 20 RIs which jointly had committed to provide 2550 days of access days, to at least 196 projects. The programme was very successful and overpassed its contractual commitments in terms of access days, projects and users by 21%, 14% and 54%, respectively. This was possible thanks to a combination of Laserlab-Europe's Dynamic Access Policy, and to several partners providing access days beyond their commitments free of charge.

Four JRAs addressed the most important scientific challenges in laser research. They substantiated Laserlab-Europe's role as the central place in Europe where the latest developments in laser research, of relevance to science, life sciences and society as a whole, are being tackled beyond the national scale. One JRA was devoted to extending the technical capabilities of state-of-the-art laser systems by overcoming key laser physics bottlenecks, two JRAs focussed on secondary radiation produced with intense lasers; short-pulse coherent radiation and energetic particles, respectively, and finally one was devoted to novel applications of lasers in modern biology and health. It is to be noted, at the end of the project, that the technical and human resources involved in these JRAs, and the amount of research accomplished and reported, significantly exceeds the contractual commitments. The JRAs clearly had a leveraging and coordinating effect on European national research efforts, extending beyond the consortium borders.

The impact of these I3 activities is manifold. TNA, as implemented by Laserlab-Europe, benefits both research infrastructures (internal impact) and the scientific User community (external). It helps maintaining the internationally leading position of the European User community in cutting-edge laser research. JRAs exploit the potential of optical technologies for new applications in science, technology, life sciences and general problems of societal relevance. Finally, networking activities are supporting measures for research, facility operations and RI development.

1.2 Summary description of project context and objectives

The overall objectives of Laserlab-Europe aim at structuring and increasing the European basis of laser RIs, reaching out to neighbouring scientific communities, tackling the most important scientific challenges in laser research, and supporting the user community through a highly co-ordinated and quality-controlled access programme.

Laserlab-Europe is the European consortium of major laser research infrastructures, forming an Integrated Infrastructure Initiative. Geographically, it covers the majority of European member states, and scientifically, it covers many areas of laser science and applications with particular emphasis on short-pulses and high-intensities. Recently this field has experienced remarkable advances and breakthroughs in laser technologies and beam parameters. Novel applications range from coherent x-ray generation, laser particle acceleration, laboratory astrophysics, and attosecond physics to fusion research, materials research, and biomedicine, to name only few. Consequently – and also as a sign of its exceptional internal coherence – the European laser community has engaged in the world's first truly international laser infrastructure, ELI. Laserlab-Europe offers unprecedented research opportunities that substantially contribute to innovation and help addressing the grand societal challenges.

Networking, Joint Research and Transnational Access play hand in hand towards the objective of structuring the European basis of laser RIs and their operation, with the balance between competition and cooperation being one of the most important structuring elements. For example, Laserlab-Europe’s “dynamic Access” policy forces the host infrastructures towards uniqueness at the European level, introducing elements of competition among them. On the other hand, they strongly cooperate within the JRA towards overall improvement of access opportunities at the European level. The JRA comprise the leading European actors from the most competitive laser research areas, drawing substantial synergies from comparably small JRA funds. Finally, a well-established but dynamically developing set of networking activities, including the “virtual infrastructure development”, user relations and training, access management, scientific and technological exchanges, foresight activities and international relations complement the inventory of RI structuring tools.

Laserlab-Europe brings together 30 leading institutions in laser-based inter-disciplinary research from 16 countries. Together with associate partners, Laserlab covers the majority of European member states, matching the geographic distribution of the scientific community.

1.2.1 Networking activities

Networking activities are the glue that binds Laserlab-Europe together. In addition, they link the Consortium to the user community on the one hand, and to the pan-European laser infrastructures on the other. They are centrepiece for establishing a pan-European “Virtual Laser Infrastructure”, one of the main objectives of the Consortium. Hence, the expected impacts include consolidation of the state of a collaboration culture between all members in the Consortium while, at the same time, establishing similar links with existing and new user communities, and with the emerging ESFRI Infrastructures. This is where Networking needs to go beyond the present state-of-the-art: increased emphasis is put on the efficient exchange and transfer of know-how through training activities, human resource development, and on enhanced collaborative research efforts among partner RIs.

To reach these goals Laserlab-Europe builds on the long Consortium experience of nurturing a balance of cooperation and scientific competition, developing best practices in the management of individual laser RIs and of the Consortium, and stimulating scientific and staff exchanges. In the present project Networking activities are adapted to react to the demands and evolution within Laserlab-Europe and the European research environment. These points are addressed as follows:

- Activities and tools for inner and outer communication and information exchange, by means of Work Packages WP2, «**Virtual Laser Infrastructure**», WP3 «**Publicity and Dissemination**», and WP4 «**Scientific and Technological Exchanges**». The latter is centrepiece to establish and extend collaborative research among all Laserlab-Europe partners. Such exchanges are based on several different tasks, including technical and JRA-related workshops to increase efficiency through knowledge sharing on different aspects of everyday research, as well as outcomes of JRAs, a Collaborative Experimental Programme for jointly conducting experimental campaigns amongst Laserlab-Europe's infrastructures, and Thematic Networks to ensure best practices and knowledge sharing amongst Ultrahigh Intensity and Ultrahigh Energy Laser operators.

- Activities for training and quality development of Users. Management of Transnational Access and Quality control of the access activities are at the core of the WP5 «**Human Resource Development**» and WP6 «**Access Management and Monitoring Infrastructures - Users Connections**». These activities allow to optimise the service to the User community, and to help the latter to increase and reach new scientific sub-communities in a cross-disciplinary perspective.

- Strategic issues concerning laser infrastructures and research within the European Research Area, including a "think-tank" activity: WP7, «**Foresight Activities**», organisation of an official network of National Contact Points WP8, «**Network of National Contact Points**», and finally allowing to lead strategic discussions and support programmes on a world scale by interaction with networks representing other global regions, and laser-related international organisations: WP9, «**Relations with non-European Laser Laboratories and Networks**».

On the whole, this set of networking activities gives to Laserlab-Europe all possible means to secure and furthermore boost the efficiency of Research and Development, whether within JRAs or for the benefit of Users of the Transnational Access activities, by pushing the Consortium members to act in a coherent and unified way, while at the same time keeping the impetus of scientific competition, both within the ERA and with respect to world competitors.

1.2.2 Transnational Access activities

One objective of Laserlab-Europe is to combine the capabilities of a comprehensive consortium of the leading European laser Infrastructures to offer European scientists research opportunities through access to an Integrated Infrastructure whose technical capability and expertise have no counterpart world-wide.

For the laser community, access is not the way to perform the bulk of research, but the top few percent of experiments which can only be done at truly unique facilities, frequently the ultimate prototype systems, giving the decisive advantage in the global competition. The concept of supporting the user community through a highly co-ordinated and quality-controlled access implementation has a strong and globally unique tradition in Laserlab-Europe, based on innovative elements like joint proposal application, joint and fully external selection, user involvement, and consortium-wide access monitoring and quality control. Proposal selection comprises a web-based application process and a common, fully external Selection Panel with an associated pool of more than 100 international referees. Laserlab's "dynamic access allocation" between host facilities takes account of fluctuations in the users' demand or access opportunities.

The Laserlab-Europe access programme offers more than 2500 experimental days, only limited by the available funds. It involves 20 research infrastructures, from 11 countries, selected on 4 criteria: quality of the installations and of research records, experience of providing access to external users, volume of the user demand and overall coherence of the set of infrastructures.

1.2.3 Joint research activities

The objectives of addressing the most important scientific challenges in the field of lasers and their applications for laser science, innovation and interdisciplinary research and, at the same time, reaching out to neighbouring scientific communities are met through four JRAs, including one from life sciences.

These JRAs react to the latest global trends in laser science and are meant to substantiate Laserlab-Europe's self-chosen role as the central place in Europe where the latest developments in laser research, of relevance to science, life sciences and society as a whole, tackled beyond the national scale, thus assisting in the development of laser research infrastructures on both the national and the European level, particularly the pan-European infrastructure ELI.

Thanks to the exceptionally short pulse durations possible using laser-like sources, over an extremely broad spectral range, the secondary sources of radiation are offering new scientific opportunities for users. Compared with free-electron lasers, laser-driven secondary sources are intrinsically synchronised with lasers. This allows to gain very rich insights into matter dynamics on unprecedented time and space scales, performing jitter-free pump-probe experiments (THz+X-rays; laser+attosecond pulses; X-ray+attosecond pulses etc.). **INREX** (Innovative radiation sources at the extremes) focuses on ongoing research (theoretical, numerical, and experimental) on and with these sources and their corresponding diagnostics. The goal is to provide unprecedented tools (beamlines) for exploring, with ultra-high time resolution and within an extremely broad frequency domain, ultrafast phenomena in physics of matter, plasma physics, biology and chemistry. Pushing the limits of secondary sources also provides important basic insights to the development and implementation of the ELI radiation beamlines.

Laser-driven acceleration of particles has opened important new perspectives for major applications in science, technology and health care. By focusing intense laser pulses onto a target it is possible to produce high quality and energetic particle beams. However, applications in these areas are hampered by the present limitations of laser-accelerated beams. **CHARPAC** (Charged particles with intense lasers) is aiming to substantially improve the control of the beam parameters such as energy, energy spread, divergence, emittance, and current, which are essential requirements for unravelling and determining potential applications. This JRA addresses several of these important questions for the case of ion and electron beams determining also fruitful basic inputs to the development of dedicated ELI particle beamlines.

Development of efficient diode-pumped solid-state laser systems capable of delivering high-energy (up to multi-kJ), short-duration pulses at multi-Hz repetition rates with an excellent temporal and spatial quality is at the core of modern laser development, and absolutely crucial for both ELI and HiPER. **EURO-LITE** (European Research Objectives on Laser for Innovation, Technology and Energy) focuses at laser physics bottlenecks crucial not only for these ESFRI infrastructures, but also for numerous other research laser systems throughout Europe. They include: (i) improving temporal contrast by several orders of magnitude; (ii) laser amplification studies on gain medium, laser-induced damage, pump source and thermal management; (iii) attosecond laser technology. Connections and cooperation with industries allow wider use, exploitation of the intellectual assets, and capitalisation of the results.

The demand and interest from the biomedical community for development and application of innovative tools needed to address open scientific issues, is continuously growing. Requests are coming from molecular and cell biology for the visualization and manipulation of single molecules and cells and for the development of tools capable to image biological processes in living animals. A high demand is also rising from medicine for the characterization of living tissues, disease diagnosis and therapy. **BIOPTICHAL** (Laser and photonics for biology and health) addresses key developments of innovative workstations and methodologies based on state-of-the-art instruments exploiting pulsed laser sources and laser-based super-resolution microscopy techniques. These activities result in a European-wide concerted effort providing new access opportunities for the biomedical community, especially for medical doctors and, thus, reaching out to new communities.

Embedded within a changing European Research Area (ERA) and positioned between single principal investigator groups on the one hand, and pan-European Infrastructures on the other, Laserlab-Europe understands itself as *the central place in Europe where new developments in laser research take place in a flexible and co-ordinated fashion beyond the potential of a national scale*. Despite the close links to the ESFRI infrastructures, there is a clear separation of tasks between them and the present Consortium. Whenever a research topic is clearly mission-specific for ELI or HiPER it is considered their task to pursue and/or finance it. When the topic is closer to basic science and of general interest for laser research and applications beyond (but not excluding) them, it is generally eligible for inclusion in the present JRA portfolio. The present JRAs have been set up with these guidelines in mind.

1.3 Description of the main S&T results/foregrounds

1.3.1 Networking activities

Networking activities addressed the overall objectives of maintaining a competitive, inter-disciplinary network of European national laser laboratories and of increasing the European basis in laser research and applications by reaching out to neighboring scientific communities and assisting in the development of laser research infrastructures on both the national and the European level.

To reach these goals Laserlab-Europe built on the long Consortium experience of nurturing a balance of cooperation and scientific competition, developing best practices in the management of individual laser RIs and of the Consortium, and stimulating scientific and staff exchanges.

I Activities and tools for inner and outer communication and information exchange:

- WP2 "**Virtual Laser Infrastructure**" comprised the project's IT services with the joint web presence and the online Access Proposal Management System, common for all access providing facilities.
  A content management system was used for the Laserlab-Europe website, allowing all participants to directly contribute to creating web pages and managing website content. It included online document repositories and databases for documentation of project results.
  The Access Activity was organised as a joint activity among all participating infrastructures, using a common advertising platform on the internet, a common call for proposals, a unified proposal processing scheme, a common external Selection Panel, and a common external pool of referees. This joint activity was supported by the online Access Proposal Management System with tools for the submission and evaluation of access applications, a reporting database for successful proposals and a user questionnaire for collecting feedback.

- WP3 "**Publicity and Dissemination**" aimed at promoting the achievements and opportunities offered by Laserlab-Europe, e.g. by publishing and presenting information material such as the highly appreciated Newsletter *Laserlab Forum*. In addition to the recurrent categories of the newsletter presenting access and other scientific highlights, Laserlab workshops and user meetings, each issue presented a special focus, such as 'Lasers for Solar Energy' and 'Lasers for Life', giving examples of a wide range of applications of laser research conducted in the Laserlab partner laboratories. Additional publicity tools were posters, leaflets and slides for advertising purposes, e.g. at major national and international conferences and summer schools, and especially for promotional activities of the Laserlab National Contact Points.
  In order to reach a broad audience, Laserlab-Europe maintained a social media web presence on Facebook, where information for the public was provided, news were spread and users and other interested persons had the opportunity to share information (www.facebook.com/laserlabeurope).
  Scientific results were documented on the Laserlab-Europe webpage through research highlights sections and through the databases for publications resulting from the JRA or from transnational access projects. The databases comprised about 470 publications from JRA and about 170 publications from transnational access projects, among them several in highly ranked journals such as Nature, Nature Physics, Nature Materials, Physical Review Letters, Science, etc.
  For the International Year of Light, a special web site was created that informed about outreach activities and specific events of the Laserlab-Europe participants throughout the year 2015: http://www.laserlab-europe.eu/events-1/light2015.

- WP4 "**Scientific and Technological Exchanges**" fostered collaborative research among all Laserlab-Europe partners and helped maintaining Europe's leading position in laser research through structured programmes of scientific and technical exchanges among infrastructures.

  Two Thematic Networks ensured best practices and knowledge sharing amongst Ultrahigh Intensity Ultrashort-Pulse and High Energy Laser operators.

The objective of the Networking Activity on Ultra-High Intensity Ultrashort Lasers (NAUUL) was to foster the exchange of knowledge accumulated over the last years with the development of ultraintense ultrashort pulse laser facilities in Europe, and to facilitate the progress of similar initiatives in countries with less experience in the field. The meetings of the network addressed the most pressing issues concerning the day-to-day operation of high-intensity lasers, i.e. pulse characterisation and control, targetry, detection of secondary radiation, etc.; the examination of the effect of target, laser and diagnostic developments of relevance for solid target interactions; and the topic of target area diagnostics with ultrafast ultraintense lasers.

One aim of the Networking Activity on High Energy Lasers (NAHEL) was to promote an efficient exchange of information on topics related to the operation of high-energy laser facilities. The annual meetings have allowed scientists from the participating laser facilities to exchange information on technical topics not often covered in scientific conferences, addressing also staff that is usually not involved in scientific communication like technical staff responsible for the routine operation of these laser facilities. Thematic meetings reaching out to the wider user and laser communities provided an exchange forum where established facilities offered their expertise in best practices and metrology, providing valuable technical input on topics related to the ELI beamlines project.

Technical workshops on topics of common interest for the Laserlab partners, such as "*Target Fabrication"*, "*Characterisation of ultra-short high energy laser pulses*" and "*Application of Laser Plasma X-ray and EUV Sources in Technology and Science*", served as platforms for the exchange of know-how and catalyst for collaborations to solve technological challenges.

Intra-Consortium exchanges of know-how were also organised by means of short-term visits in order to enhance the transfer of knowledge, technical know-how and/or good practice between partners of Laserlab-Europe and to reinforce scientific collaborations.

II Activities for training of users and access quality development:

- WP5 "**Human Resources Development**" helped to increase the User community and reach new scientific sub-communities in a cross-disciplinary perspective by addressing potential users and providing training in experimental skills that are crucial in specific areas of laser science. Three Training Schools for potential or new users were organised, focussing on *Biophotonics*, on *Laser Applications in Spectroscopy, Industry and Medicine* and on *Light-based Technologies and their Applications in Chemistry, Material and Sensoric Sciences and Biomedicine*. In addition, four international laser-related training schools were supported, dealing with *OPCPA Training*, *Advanced X-ray Spatial and Temporal Metrology*, *Laser Applications at Accelerators* and with *Lasers in Materials Science*.

  For the *User Training for Bio-Optical Techniques*, related to the JRA BIOPTICHAL and subcontracted to CLL in Coimbra, Portugal, calls for proposals were published resulting in 11 short-term training visits with 109 experimental laser training days. During these training visits, scientific projects were performed, which resulted in eight scientific publications and several manuscripts already submitted or in preparation.

  Collaboration with FELs of Europe and the ESFRI project ELI – Extreme Light Infrastructure aimed to develop joint programmes of exchange and training.

  In addition, Laserlab-Europe members participated in several FP7 and H2020 projects for outreach activities related to photonics, addressing schools, universities, museums, media, industry, hospitals, etc. Communicating the impact and fascination of photonics to young talents was an opportunity to create interest in a career in science, thus helping to expand the basis of human resources in the field of laser research and industry.

- WP6 "**Access Management and Monitoring Infrastructures-Users Connections**" allowed optimising the services to the user community through joint management and monitoring of the Access activities with substantial involvement of User Representatives. Access to the Laserlab Research Infrastructures was provided in a highly coordinated way, which provided the flexibility to respond to user needs and new developments and ensured the full availability of the best European resources for the user community. The consortium-wide unified access policy comprised a web-based application process for projects, a common, fully external Selection Panel with an associated pool of more than 200 international referees and a dynamic access allocation taking account of fluctuations in the Users' demand.

A User Representatives Committee was elected at the beginning of the project. The members participated in the different project boards and acted as interface between the user community and Laserlab-Europe. They co-organised the annual user meetings that usually gathered 50-60 participants and provided a platform for the access providers to present recent upgrades, new experimental set-ups or diagnostics, and for the users to present their scientific results and to provide their feedback.

In addition, users' feedback was collected regularly through a *User Questionnaire*, which Users were asked to complete after finalising their access projects. The feedback allowed to monitor and improve the quality of the Laserlab access activity, especially with regard to access publicity, submission and selection procedures and services provided, including facility operation and safety.

III Strategic issues concerning laser infrastructures and research within the European Research Area ERA:

- WP7 "**Foresight activities**" was a "think-tank" activity on strategic scientific issues and aimed at addressing European "Grand Challenges" through Foresight Workshops as well as other Network activities. A Foresight Workshop on *"Lasers for Life"* was organized in 2014 in London, UK, featuring lectures from leaders in the application of lasers to biology and medicine, and bringing together two different communities; clinicians using lasers for disease diagnosis and treatment, and experts in the design and use of lasers and associated optics. The workshop was attended by 140 delegates, including 70 from Laserlab-Europe institutions, and ended with a panel discussion where delegates were invited to give their views on the future of the area. In addition, cooperation with FELs of Europe and the ESFRI project ELI – Extreme Light Infrastructure was pursued in order to explore synergies and avoid duplication of efforts. As an outcome, co-organisation of workshops and trainings of the different communities was planned, and a joint proposal for a Horizon 2020 grant for collaboration on topics of common interest, exploring synergies, strategies and foresight activities promoting advanced laser RIs in Europe was successful.

- WP8 "**Network of National Contact Points**" represented Laserlab-Europe within the national scientific communities and helped to receive support to extend laser infrastructures to the whole EU area. A major success was the selection of The Laboratory for Intense Lasers (L2I) at Laserlab-Europe partner IST, Lisbon, for the Portuguese Roadmap of Research Infrastructures.

- WP9 "**International Relations**" facilitated strategic discussions and support programs on a world scale by interaction with networks representing other global regions and laser-related international organisations. Contacts have been established with African Laser Networks, in particular the *African Laser*, *Atomic, Molecular & Optical Sciences Network* (LAM Network, www.lamoptinet.org), the *African Laser Centre* (ALC, www.africanlasercentre.org), the African Spectral Imaging Network (AFSIN, https://sites.google.com/site/multispectralmicroscopy).
  Latin America has a strong research infrastructure with many centres covering a vast range of scientific topics. The Laserlab-Europe participants were reinforcing the relations with Latin-American partners by promoting training and access possibilities and by fostering interaction with these networks, especially in the field of research with ultrashort and intense lasers.
  On specific research areas Laserlab cooperated closely with the IUPAP committees ICUIL, the *International Committee on Ultra-High Intensity Lasers*, and Laserlab members participated actively in the biennial International ICUIL Conference. Contacts and collaboration with the Asian Intense Lasers Network AILN, which focuses on intense lasers, occurred mainly within the framework of the *International Committee on Ultra-High Intensity Lasers* ICUIL.

1.3.2 Transnational Access activities

***One objective of Laserlab-Europe was to combine the capabilities of a comprehensive consortium of the leading European laser Infrastructures to offer European scientists research opportunities through access to an Integrated Infrastructure whose technical capability and expertise have no counterpart world-wide*.**

For the laser community, access is not the way to perform the bulk of research, but the top few percent of experiments which can only be done at truly unique facilities, frequently the ultimate prototype systems, giving the decisive advantage in the global competition. The concept of supporting the user community through a highly co-ordinated and quality-controlled access implementation had a strong and globally unique tradition in Laserlab-Europe, based on innovative elements like joint proposal application, joint and fully external selection, user involvement, and consortium-wide access monitoring and quality control. Proposal selection comprised a web-based application process and a common, fully external Selection Panel with an associated pool of more than 100 international referees. Laserlab's "dynamic access allocation" between host facilities took account of fluctuations in the users' demand or access opportunities.

The Laserlab-Europe access programme involved 20 research infrastructures, from 11 countries, selected on 4 criteria: quality of the installations and of research records, experience of providing access to external users, volume of the user demand and overall coherence of the set of infrastructures.

In total, 3073 experimental days were provided to 673 users. The dynamic access allocation allowed for a flexible readjustment of the overall access offer to users, and together with considerable co-funding from other resources the actual provision of access exceeds the initial estimates by 21%. This result demonstrates the value of the highly coordinated, network-wide and flexible implementation of the access programme within Laserlab-Europe.

Overall achievements of the Laserlab-Europe transnational access programme

The Laserlab-Europe Transnational Access (TNA) programme involved 20 infrastructures which jointly had a commitment for providing 2550 days of access days over the contract duration (42 months). It was anticipated that at least 196 projects would be carried out by more than 436 users.

From the start of the contract, the access programme of Laserlab-Europe has been extremely successful and systematically ahead of schedule. Table 1 displays the status of the Laserlab-Europe access programme at the end of the contract. The achievements are compared with the contract commitments.

	Contract Commitments	Achievements	Ratio Achievement/Contract
Access Days provided	2550	3073	121%
Projects carried out	196	224	114%
Users received	436	673	154%

Table 1: status of the Laserlab-Europe access programme at the end of the contract

The data in Table 1 show that the Laserlab TNA programme overpassed its contractual commitments in terms of access days, projects and users by 21%, 14% and 54% respectively.

The progression of the performances of the Laserlab access programme over the whole contract duration is displayed on Figure 1. It is remarkable that the access rate provision has always been ahead of schedule (i.e. above the dotted red line corresponding to a constant rate provision) and has even accelerated during the 3rd reporting period.

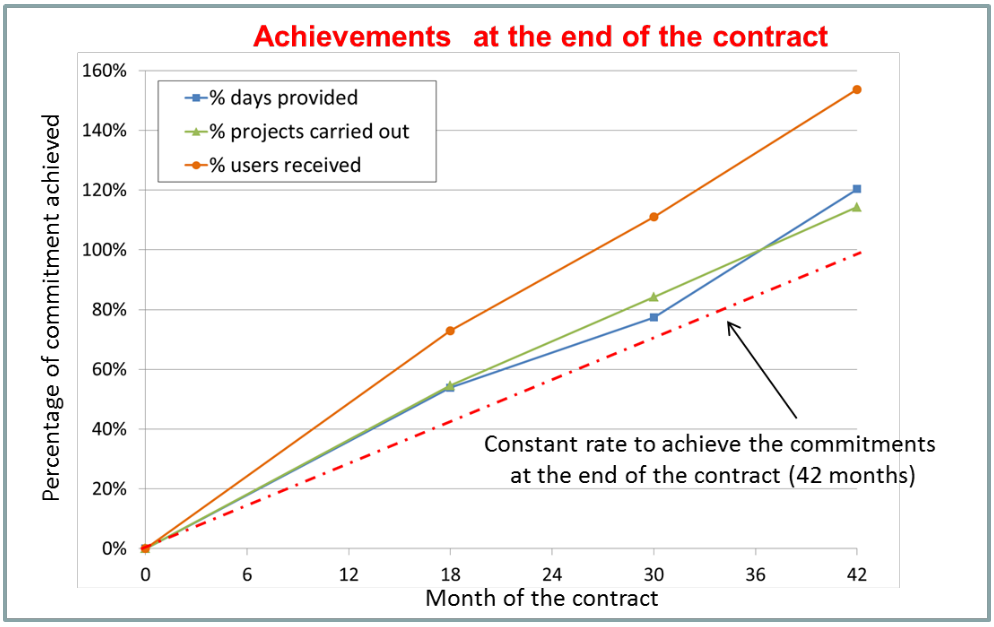

Figure 1: progression of the Access programme over the full duration of the contract

The evolution of the number of projects performed at Laserlab installations follows closely the progression curve for the access units, meaning that the average duration of a contract (13,7 days) had been properly evaluated in advance by Laserlab-Europe (13.0 days).

Finally, all over the contract duration, Laserlab-Europe infrastructures attracted significantly more users than initially expected in the contract. This can be explained in several ways : 1) the experiments carried out were more and more sophisticated and required the participation of several scientists with complementary expertise; 2) laser science is now spread in many research, technical and industrial domains and becomes more and more attractive to young researchers; 3) the big laser projects like the Extreme Light Infrastructures and many other European projects require hundreds of laser technicians and scientists, and Laserlab-Europe was the place to train them.

Access programmes of Laserlab-Europe partners

All the 20 Laserlab infrastructures that had commitments for providing access did so. Out of them, 15 infrastructures (GSI-PHELIX, ICFO, LP3, CELIA, LULI, PALS, VULRC, CLF, CUSBO, SLIC, LLC, MBI, ULF-FORTH, LLAMS and LENS) provided more access units than their contractual commitments. Three infrastructures that offer in particular access to facilities for life science (LENS, LLAMS and ULF-FORTH) have even provided about 100 access days more than their commitments.

This change with respect to the expectations indicated in the contract was made possible by the Laserlab Access Policy: in order to adapt its access programme to the user demand, Laserlab's Dynamic Access Policy allowed transferring access days from installations whose access programmes were behind schedule towards installations for which the user demand was the highest. The Access Board therefore updated in March 2015 the amounts of access units allocated to the Laserlab-Europe infrastructures, on the basis of the access already provided, or anticipated from received proposals.

These figures show that the general success of the Laserlab-Europe access programme is the sum of the high performances and attractiveness of the individual participating facilities and that the reallocations globally favoured the infrastructures involved in life sciences.

Scientific outcome

The Laserlab-Europe transnational access opportunities led to scientific progress beyond the state-of-the-art that can best be judged by the scientific output and impact. At the time of finalising this report, the experiments performed during the project have yielded 163 publications (papers in peer-reviewed journals, book chapters and articles in proceedings of conferences), several of them in high ranking journals such as Physical Review Letters or those belonging to the Nature publishing group. In view of the delay between completion of an access project, submission of a paper and actual publication, this number is bound to rise considerably in due course. Selected highlights of important research results from the user projects are published regularly in the Laserlab Newsletter.

Conclusion

The Laserlab-Europe access programme has been extremely successful. The contract commitments were reached 6 months before the end of the contract, whereas 15 among the 20 access providing infrastructures widely overpassed their access commitments. In order to offer the best service to its users, Laserlab-Europe maintained its access activity until the end of the contract thanks to financial contributions of the access providing infrastructures.

Laserlab-Europe was more and more attractive to users: 670 users were received during the contract, which are about 230 users beyond expectations. The Travel & Subsistence expenses of ALL users were reimbursed thanks to different mechanisms of budget reallocations.

Laserlab-Europe’s access activity will be enhanced in the new H2020 contract with the participation of additional installations including two Free Electron Lasers to further extend the Laserlab offer and reach an even larger user community.

1.3.3 Joint research activities

The objectives of addressing the most important scientific challenges in the field of lasers and their applications for laser science, innovation and interdisciplinary research and, at the same time, reaching out to neighbouring scientific communities were met through four JRAs, including one from life sciences.

These JRAs reacted to the latest global trends in laser science and were meant to substantiate Laserlab-Europe’s self-chosen role as the central place in Europe where the latest developments in laser research, of relevance to science, life sciences and society as a whole, are tackled beyond the national scale, thus assisting in the development of laser research infrastructures on both the national and the European level, particularly the pan-European infrastructure ELI.

1.3.3.1 WP30 – Laser and Photonics for Biology and Health (BIOPTICHAL)

1.3.3.1.1 Executive Summary

Over the last years pulsed laser-based techniques developed in fundamental laser sciences, such as harmonic generation and Multi-Photon (MP) excitation, have found their applications in biophysical research, as non-invasive tools for the imaging and manipulation from single molecules to cells and tissues, with unprecedented resolution and penetration depth. The demand from the biomedical community for application of these tools and development of new ones, as well as the need to address open scientific issues, is continuously growing, and is providing new opportunities for industries. An increasing request is coming from molecular and cell biology for the visualization and manipulation of single molecules and cells and for the development of tools apt to image biological processes in living animals. A high demand is also rising from medicine for the characterization of living tissues, disease diagnosis and therapy.

A high expertise in these fields exists at the facilities that participated in the JRA on Laser and Photonics for Biology and Health (BIOPTICHAL), which aimed at uniting the forces to generate excellence and open novel research and job opportunities. This JRA has provided at the same time a European-wide concerted effort to improve methods exploiting pulsed laser sources in biomedicine and provide access to the biomedical community to state-of-the-art instruments. The project reached a wide user basis, especially in the medical doctor community, and connections and cooperation with industries allowed wider use, exploitation of the intellectual assets, and capitalising of the results. The project was focussed on three main objectives addressing key developments of innovative workstations and methodologies, ranging from the investigation of single bio-molecules and single cells to *in vivo* microscopy on living animals and to the development of diagnosis tools for human diseases.

The first objective of the project (Nanobiophotonics) was to address the need of efficient handling, manipulation and visualization of tiny biological objects such as individual cells, molecules, and biocompatible materials to simultaneously perform advanced optical and mechanical measurements on them.

The development of advanced imaging workstations, beyond what is commercially available, as well as novel methodologies for the investigation of living cells and animals was the second objective of the JRA (Advanced Microscopy). In particular, the JRA partners made a concerted effort toward extending spectral excitation range, penetration depth, sensitivity, and selectivity, temporal and spatial resolution.

An important step forward, from laboratory to *in vivo* and clinical applications, was made by the partners in the third project objective (Biomedical Imaging). Both biomedical diagnostics and laser-based therapies greatly benefited from the use of short pulse lasers, allowing deep in-vivo measurements and manipulation. New tools and methods for *in vivo* non-invasive clinical diagnostics have been developed based on non-linear, time-resolved and advanced microscopy, and on the study of photon propagation in biological tissues by short pulse spectroscopy. Diagnostic capabilities have been enhanced by combining multiple approaches. The increased sensitivity, flexibility, and real-time response of those novel techniques will facilitate their use in clinical applications. The optical biomedical research activities are strongly increasing worldwide, and it is very likely that many user groups are attracted to this application being in the field of cancer diagnostics and therapy.

1.3.3.1.2 Description of the main S&T results

The BIOPTICHAL joint research action has been focussed, as a first objective, to realize workstations and techniques to efficiently manipulate and analyse biological samples from the single molecule up to the single cell level. High-speed optical tweezers have been developed at LENS, the European Laboratory for Non-linear Spectroscopy in Florence, Italy. These optical traps allow probing bio-molecular interactions and protein conformational changes on a sub-millisecond time scale, one molecule at a time (Capitanio, M. et al., *Nature Methods*, **9**, 1013–1019, 2012). Constant loads can be applied between a binding protein and an intermittently interacting biological polymer with a measurement delay of only ~10 μs, allowing the detection of interactions as brief as ~100 μs and sub-nanometre conformational changes with a time resolution of few tens of microseconds. The high-speed optical tweezers were used to investigate molecular motors, directly measuring load-dependence of a single muscle myosin molecule, and DNA-binding proteins, to study sequence-dependent interactions of transcription factors to DNA. Such developments open new avenues for investigating the effects of forces on biological processes. LENS also developed novel methodologies to extend localization and tracking of single molecules to three dimensions in living cells (Gardini L, et al., *Sci Rep* **5**,16088, 2015) and combined manipulation and tracking of single molecules, applied to the study of gene expression regulation.

ICFO, the Institute of Photonic Sciences in Barcelona, Spain, developed plasmonic nano-structures with enhanced optical fields for in-plane optical manipulation of tiny biological specimens and enhanced sensitivity for bio-molecule detection, in particular for single molecule detection of biological samples at ultra-high concentrations. Such antenna probes demonstrated superior performance compared with sub-wavelength probes, in terms of excitation field enhancement and confinement (D. Punj et al., *Nature Nanotechnol.* **8**, 512-516, 2013; M. Mivelle et al, *Nano Letters* **12**, 5972, 2012). A clever hybrid nano-antenna probe based on a monopole antenna engineered on a bowtie nanoaperture allowed ICFO researchers to reach 20nm true optical resolution together with unprecedented angstrom localization accuracy on the coordinates position of individual fluorescent molecules (M. Mivelle, et al, *Nano Lett.* **14**, 4895, 2014). Together with EPFL collaborators, ICFO fabricated large arrays of nanoaperture-based antennas that were used as hotspots of localized illumination to excite fluorescently labelled lipids on living cell membranes (V. Flauraud et al., *Nano Letters*, **15**, 4176, 2015). A large number of applications of these inexpensive and fully biocompatible antenna arrays is foreseen, including the investigation of the plasma membrane of living cells with nanoscale resolution at endogenous expression levels. ICFO also realized various fiber-based resonant dipole and nanogap optical nanoantennas for extreme resolution optical microscopy achieving an optical resolution down to 40 nm, far below the Abbe diffraction limit (A. Singh et al, *Nano Lett.* **14**, 4715-4723, 2014).

LENS, ICFO, and FORTH (Foundation for Research and Technology – Hellas, in Crete, Greece) developed Multi-Photon (MP) microscopy combined with MP nanosurgery for the selective disruption of sub-cellular structures. In particular, LENS applied this technology to investigate the reactive plasticity of the central neuron system *in vivo* in models of neurodegeneration (Allegra Mascaro, A.L. et al., *PNAS* **110**, 10824-9, 2013). FORTH and the Laser Research Centre at Vilnius University, Lithuania (VULRC) have been involved in the development of technologies for multi-photon (MP) polymerization. Among the various applications, VULRC set up methodologies to produce regular matrices of biological molecules and FORTH generated biomimetic 3D scaffolds, particularly for bone regeneration, using organic-inorganic hybrid and biodegradable photopolymers for tissue engineering and regenerative medicine applications.

In the second objective of the project, through the development of advanced microscopy workstations and methodologies, the partners were able to extend penetration depth, temporal and spatial resolution, non-label-methodologies and application to living cells and animals, for the benefit of European users.

Light-sheet microscopy has seen great developments in the last years because of the capability to image large samples (whole organs or entire small animals such as zebrafish) at high resolution. A light sheet microscope was developed by LENS to image whole mouse brains with microscopic resolution. An innovative design, in which light sheet illumination is coupled with confocal slit detection, improved contrast and signal-to-background ratio. This approach, which we called confocal light sheet microscopy (CLSM) has been demonstrated by reconstructing the complete neuroanatomy of Purkinje cells in the mouse cerebellum and by tracing mm-long axons in the unsectioned mouse brain (Silvestri et al., *Opt Exp* 2012). LENS activity was also focused on the improvement of state-of-the-art clearing methods that, by making the samples transparent, allow imaging of such large areas. A new solution was developed that is well suited both for direct clearing of small portion of nervous tissue and for clearing entire murine brains (Costantini I. et al., *Scientific Reports* **5**:9808, 2015).

Single molecule and super-resolution microscopy have been developed by the groups participating in BIOPTICHAL to increase detection sensitivity and spatial resolution of microscopy workstations that are now available to the European community. A 5-colour single molecule workstation together with super high resolution has been developed at the Central Laser Facility (CLF) at the STFC Rutherford Appleton Laboratory in the UK, and it is now available as a European facility. Two state-of-the-art 3D super-resolution microscopes based on SIM (Structured Illumination Microscopy) and STORM (Stochastic Optical Reconstruction Microscopy) are now available, supported with staff dedicated to the facility. A 5-colour single molecule workstation based on Total Internal Reflection Fluorescence (TIRF) is now in operation and is available to users. ICFO worked on developing super-resolution techniques, such as Stimulated Emission Depletion (STED) microscopy and STORM microscopy combined with single molecule imaging. In particular, ICFO developed a correlative imaging approach that combines live-cell single particle tracking with fixed cell super-resolution microscopy (S. Balint et al., *PNAS*, **110**, 3375-3380, 2013). This approach allows the achievement of high temporal (ms) and high spatial (10-20 nm) resolution such that dynamic context can be combined with ultrastructural information. Also, a new imaging technique has been developed at ICFO, which combines dual-colour single molecule dynamic data at high temporal resolution to re-construct super-resolution cartography maps of cell membrane regions explored by molecular components (J. A. Torreno-Pina et al. *PNAS* **111**, 11037, 2014). The Institute of Optoelectronics in the Military University of Technology (MUT-IOE), Warsaw, Poland, exploited a compact laser plasma source to develop a desk-top soft X-ray microscope. The microscope, operating in the “water window” spectral range and based on a laser plasma soft X-ray source, has been tested showing half-pitch spatial resolution of 60nm.

Optical non-linear phenomena have been used by several Laserlab partners to develop novel non-linear microscopes such as Two-Photon, Second and Third Harmonic Generation (TP, SHG and THG) microscopy. This research allowed extending spectral excitation range, penetration depth, sensitivity, and selectivity, as well as the imaging of non-labeled samples and was focussed on developing novel methodologies to investigate living cells and animals.

The application of laser light for *in vivo* imaging was pursued in the third objective of the project. FORTH has been working on fluorescence diffuse optical tomography; STFC-CLF has combined picosecond-FLIM with microsecond PLIM (phosphorescence lifetime imaging). UL (University of Latvia), in collaboration with the International Laser Centre in Bratislava, Slovak Republic (ILC), have developed an experimental methodology for parallel point measurement of tissue fluorescence lifetimes (FLT) and photo-bleaching rates. Politecnico di Milano, Italy (POLIMI) has completely assembled and tested a Time-gated Optical Projection Tomography (TGOPT) microscope, a new technique developed in the POLIMI labs with a contrast greatly improved compared to CW imaging.

Within the same objective, novel optical tools and methodologies for the study, diagnosis and therapy of human diseases were developed. LENS focused its research on early diagnosis of skin cancer, as well as investigating the molecular basis of Alzheimer's disease and cardiac pathologies. In particular, LENS used MP random access microscopy in combination with novel voltage sensitive dyes to probe action potential propagation and calcium release across the tubular system of cardiac cells. By exploiting this technique, LENS investigated the role of T-tubule remodelling in the electro-mechanical dysfunction associated to hypertrophic cardiomyopathy (HCM) in a mouse model that expresses a clinically-relevant HCM mutation. Although T-tubule structural remodelling in this mouse model myocytes was found to be modest, T-tubule functional defects determined non-homogeneous Ca^{2+} release and delayed myofilament activation that significantly contribute to mechanical dysfunction (Crocini C. et al., *PNAS* **111**, 15196-15201, 2014)

The Institute for Lasers, Life and Biophotonics Amsterdam, Netherlands (LLAMS) pursued the development of a catheter-based system for comprehensive imaging of lung tissue in the main airways and the parynchemia (Jianan Li et al., *Optics Express* **23**, 3390–3402, 2015). OCT was combined with auto-fluorescence bronchoscopy to define sensitivity and specificity of OCT for the identification of lung cancer in collaboration with the VU University medical centre. ICFO and Lund University, Sweden (LU) developed systems to monitor response to photodynamic therapies.

Finally, POLIMI, ICFO, and LU have been working on the development of workstations exploiting time-resolved spectroscopy (TRS) and diffuse correlation spectroscopy (DCS) towards clinically oriented applications. A broadband time-resolved diffuse spectroscopy workstation is now functional for clinical use. In particular, the system was optimized for all safety features (e.g. laser safety, electrical isolation) compatible with clinical use. Particular emphasis was also given on robustness and reliability of measurements to permit smooth operation outside the laboratory for non-expert personnel. The system was characterized using phantom materials and of tissue absorbers.

1.3.3.1.3 Potential impact

Common to all the research and developments within the joint research action BIOPTICHAL is the relevance to modern biology and medicine. The novel technological and methodological developments pursued by this JRA were effectively carried out through an extensive cooperative work, exchange of knowledge, and dissemination of the results between the participants. The user basis was extended outside the borders of the consortium, especially towards the biologist and medical doctor communities, through involvement of associate medical partners and European medical societies and dissemination of the results in biological and medical conferences. The objectives pursed by the present JRA were also aimed at creating substantial technical developments for research and diagnostic tools. Connections with industries allow the exploitation of such developments to capitalize the results and create new opportunities for research and jobs. Connections with hospitals and clinics have allowed, and will even more in the future, the test of the diagnostic and therapeutic tools developed through this JRA directly on patients. Moreover, a network formed by associated groups working on specific topics and hospitals has boosted the development of specific deliverables and brought additional value to the project.

The achievements of the collaborating infrastructures within the present JRA will spread also to other members of Laserlab-Europe. Research in the field is being pursued also outside the European Union, and it is extremely important that European researchers are at the forefront in this highly competitive field.

1.3.3.2 WP31 – CHARged Particle ACceleration with intense lasers (CHARPAC)

1.3.3.2.1 Executive Summary

Laser-plasma accelerators are one of the most exciting applications of high intensity lasers, and in recent years we have observed significant progress worldwide, not only in scientific terms but also in the exploration of different potential avenues for applications driven by the secondary particle sources generated with high intensity lasers.

The teams participating in CHARPAC have provided worldwide leadership in the field, leading many of the exciting developments in the field and CHARPAC has directly contributed to improve the properties of electron and ion beams produced by the interaction of intense laser pulses with matter. Moreover, the advances associated with CHARPAC have paved the way for the next generation of laser-plasma accelerators that will be focused on the applications of the secondary sources. Highlights of the contributions and major results of the different groups provide clear case studies of the key advances of CHARPAC and their scientific and societal impact.

1.3.3.2.2 Description of the main S&T results

The main objective of CHARPAC was to undertake a clear and focused investigation to improve the properties of electron and ion beams produced using intense laser pulses. The work in CHARPAC was split into two tasks that were dedicated to electron and ion beam improvement, respectively. The main goals for each task were described as:

Task 1: Electron beam improvement via enhanced generation of electron beams by self-injection and/or stimulated injection of electrons from the plasma with an additional laser pulse or with shaped gas targets. The outcome of the studies was aimed at the improvement of the plasma wakefield accelerator stability and in helping to evaluate its scalability for future projects of interest to the high-energy physics community, for the design of compact free-electron lasers and their numerous applications.

Task 2: Ion beam improvement with the foremost objectives being to improve the maximum energy, to reduce the energy spread, and to increase the collimation of the ion beam, at high repetition rate. Of particular relevance was the production of high-dose, high-energy (> 120 MeV) collimated and spectrally selected ions.

Overall, the outlined goals of CHARPAC have been fully achieved within the technological constraints of the available laser technology; in many of the topics the outcomes have clearly exceeded the initial goals of the JRA. The main overarching achievements of CHARPAC have been a significant optimization and control of electron and ion acceleration via novel engineered targets and the fine control of laser beams. These achievements are evident both in electron acceleration, resorting to shock generated steep gradients in gas jets and capillary tubes, that have been explored to optimize the beam properties, and in ion acceleration, with nanoengineered targets (foams, microspheres, gratings, foils) and engineered lasers (multiple pulses, phase controlled ultrashort pulses), that are now moving ion acceleration into highly optimized TNSA regimes, collisionless shock acceleration and radiation pressure acceleration. The quality of the results is evident not only from the training of young scientists that CHARPAC has provided but also from the numerous high profile scientific publications and patents that have resulted from CHARPAC.

1.3.3.2.3 Potential impact

Europe maintains a strong and leading position in the field of secondary sources driven by intense lasers. Some of the results of CHARPAC are at the core of the most important advances in this field. CHARPAC has contributed to maintain the European leadership and has served as an important pool of resources and a forum for the key teams in the field.

The scientific impact has been tremendous, not only in terms of publications but also in terms of training of students and post-docs. This is critical for the future of the field in Europe given the large number of facilities in Europe already deployed or soon to be deployed that will require a significant amount of trained person power. Examples of these facilities are, for instance, APOLLON (France) and the three ELI Pillars (Czech Republic, Hungary, Romania).Moreover, the teams involved in CHARPAC have also pooled their resources to participate in large EU projects, e.g. EUPRAXIA, and CHARPAC was an important integration forum for the scientific community working on these topics.

The teams in CHARPAC have also contributed to the development of new instrumentation and diagnostics for the different user communities and facilities. This has been particularly evident in Task 2, on ion acceleration.

Examples from the different laboratories are presented below, without aiming to be exhaustive. Detailed reports, including the main scientific outcomes can be found in the periodic reports and in the various deliverables of CHARPAC.

Research of high-intensity laser-plasma interactions is decidedly multi-disciplinary. PhD students and young researchers must master many aspects of physics and engineering in order to succeed. For example, all students involved in the activities of CHARPAC (and a good example is the plasma acceleration group at the LLC) learned the key aspects of laser-plasma interactions and in many cases, such as at LLC, they operated and maintained a multi-terawatt laser system. Therefore, they received considerable training in advanced optics and laser technology and several of the PhD students work in the photonics industry (i.e. optics and laser development) after their graduation. Through hands-on experience with energetic charged particle beams, they also received practical training in nuclear- and accelerator physics and instrumentation, and several graduated PhD students currently work at accelerator facilities (e.g. the MAX IV-laboratory in Lund and DESY in Hamburg).

At the Lund Laser Centre, LLC, Sweden, the CHARPAC JRA played a vital role, both in creating new and in consolidating existing transnational scientific collaborations. For example, a series of experiments to study and to improve the stability of laser-accelerated electron beams were performed at LLC. The experiments involved researchers from LLC, CEA-SLIC (France) and Université Paris-Sud (France) and the joint work resulted in several scientific publications. In a joint experiment between LLC and LOA, performed at LOA during 2015, controlled injection of electrons in a laser-plasma accelerator was studied using a sharp density transition. Finally, as a result of discussions at a CHARPAC JRA meeting, a fruitful collaboration was established between CEA-DAM and the LLC to study laser-plasma interactions using the particle-in-cell simulation code CALDER-CIRC.

The contribution of CEA-CESTA to the JRA CHARPAC was based on the theoretical and numerical investigation of particle acceleration, and has mainly led to impacts on science and on the scientific community. Indeed, the results obtained within this project have mainly been used to explain and support the experiments conducted by collaborators involved in the JRA CHARPAC.

The work at CEA-SLIC has mainly given a contribution to the knowledge of structured target influence on laser-matter energy coupling efficiency and to the development of relativistic plasmonics, opening a new field of investigation and, likely, providing new paths for high energy density and high intensity physics applications in future. The main research activity of CEA-SLIC in this JRA framework has been the result of two consecutive international collaborations including laboratories from France (LULI, LSI, Université Paris Sud), Italy (Universita' di Pisa, INO, POLIMI) and the Czech Republic (FNSPE). The complementarity of the skills and interests of each participant allowed the collaboration to cover multiple sides of this research (target manufacturing, experimental activity, numerical simulation, theory).

For the SPRINT team of LULI, the impact on science has been positive, allowing to progress toward high-repetition rate operation (both for the production and diagnostics) of the generation of laser-based ion beams, which will directly and positively impact the operation of the future Apollon laser facility that will open in the Saclay area to users in 2017. Also, the generation of optimized neutron beams based on ions will open the possibility for time-resolved neutron radiography at the ns scale, which was impossible up to now. Also, the advances permitted within CHARPAC will benefit a recently created company offering systems for laser facilities and which has a tech-transfer agreement with LULI.

At CEA-LOA the pros and cons of different injection techniques allowing to produce high-quality electron beams with interesting parameters (charge, maximum energy, energy spread and divergence) for numerous applications while achieving a good stability and reproducibility have been investigated. Transverse self-injection is the most easy to achieve, but is intrinsically unstable and does not allow for a very precise parameter control. Sharp density transition injection may be useful for various applications requiring good stability and low energy spread with a low charge (for instance as an injection stage for multi-stage LWFA). Ionization injection in pure high Z gases allows producing very stable, heavily-charged low energy beams with very large energy spread.

The potential impact of these results is important for the scientific community not only in terms of impact in science but also for industrial applications. Each explored scheme of laser plasma accelerators produces an electron beam that has optimized parameters depending on their uses for applications. These results have also been important for creating synergies between European groups and in the preparation of the new JRA of Laserlab IV that will be more focused on medical applications of laser plasma accelerators.

At HZDR the work was focused on development and detailed analysis of the Thomson backscattering source at the radiation source ELBE (or in the future any other laser driven electron source) allowing for the provision of the source as a future user installation at the user facility ELBE (research infrastructure improvement).

Within the CHARPAC programme new collaborations between MBI, LOA and POLIMI have been set. Long standing collaboration with a partner belonging to groups of University of Belfast/ELI-Prague (now GIST Korea) has been continued. Results were obtained in the context of steering of ion charge in specific laser driven acceleration experiments and following ion beam manipulation. Impact can be recognized concerning basic scientific questions which are related to the possible development of new compact and short pulse fast positive/negative ion as well as neutral atom sources. Multi-laser beam experiments are of great relevance for ELI. In addition, for the scientific community a dual beam high power laser system is of great interest.

These brief examples illustrate the multilateral and collaborative efforts within CHARPAC, not only in scientific terms, with many joint publications, but also as a leverage to ambitious and fruitful collaborations that have and will continue to have impact in the main scientific and technological developments in the field of laser-plasma accelerators. CHARPAC has also contributed to the training of many PhD students and post-docs that are now involved in many exciting laser infrastructures in Europe and others in the photonics industry. Furthermore, the optimization on the sources has clearly paved the way for the applications that will be pursued in future and ongoing pan-European projects that will address now the challenges associated with applications.

1.3.3.3 WP32 – Innovative radiation sources at the extremes (INREX)

1.3.3.3.1 Executive Summary

Over the last few years, the rapid evolution of femtosecond lasers towards ultra-high intensities and single optical cycles has revolutionized the generation of high intensity radiation over the whole electromagnetic spectrum from THz to hard x-rays. Thanks to the short pulse durations produced using laser-like sources, which has been extended below 100 attoseconds, and the large number of photons per pulse (up to 10^{14}) over an extremely broad spectrum, these secondary sources are now regularly producing new scientific opportunities. These laser-driven secondary sources are intrinsically synchronised with lasers. This offers very rich insights into matter dynamic on unprecedented time and space scales, by allowing jitter-free pump-probe experiments (THz + X-rays; laser + attosecond pulses; X-ray + attosecond, etc.).

The goal of the JRA “Innovative Radiation Sources at the Extremes” (INREX) was to further develop and apply these sources and their associated diagnostics in a structured and collaborative programme coordinating the theoretical, numerical, and experimental efforts. The development of secondary sources with properties that are pushed to the limit were also meant to contribute to the scientific basis for the ELI Attosecond and ELI Beamline projects.

INREX can be considered an extremely successful JRA in terms of meeting these goals, producing groundbreaking scientific results and carrying out joint research of the partners. The great number of partners and the variety of topics – from THz physics to X-ray physics – seemed to be a challenge. But as it was planned, the exchange of knowledge from different scientific fields that took place at the INREX-meetings turned out to be extremely seminal.

1.3.3.3.2 Description of the main S&T results

INREX had 10 Objectives, which were, as stated at the start of the project:

1. Few-cycle to single cycle mid-IR sources: The objective was to develop high energy nearly single cycle pulses in the mid-IR, allowing strong field studies in this spectral region.

2. Ultra-short and intense THz sources: Here Laserlab-Europe targeted the implementation and/or the improvement of tabletop ultra-short and intense THz sources.

3 Improving attosecond pulses photon energy, flux and repetition rate: Conversion efficiencies for the generation of isolated ***as*** pulses in gases were to be optimised in different wavelength regions. The repetition rate was to be increased to several 100 kHz or MHz.

4. XUV optics, detection and diagnostic techniques: Laserlab-Europe participants planned to develop *ultra broadband* ($\Delta\lambda/\lambda \sim 1/3$) XUV optics, which preserve or even correct the *temporal* and *spatial phases* of the HHG beam.

5. Ultrafast XUV metrology/spectroscopy in atomic, molecular and solid state physics: The objective was to develop techniques to apply ultrafast (phase-controlled) laser sources to pump-probe studies in atomic and molecular systems, ranging from pump-probe experiments involving photons and electrons as probes and pumps and vice-versa, with arbitrary wavelengths.

6. Synchrotron sources and free-electron lasers based on laser plasma wakefield accelerators: The main objective of this task was to pool experimental and theoretical efforts across the various groups to realise a LPWFA driven FEL. This involved developing both LWFA and beam transport systems and investigating the short pulse regime in the FEL.

7. Plasma and electromagnetic wigglers based on laser-plasma interactions: The very large transverse forces of a laser driven plasma density wake can act as a strong plasma wiggler. Relativistic electrons inside the "bubble" shaped wake will oscillate in its electrostatic potential and radiate very strongly. This so called "betatron" radiation is emitted as a very large spectrum. Several possibilities were to be explored to obtain shorter wavelengths with modest laser pulse energies.

8. Realize ultra-intense lasers at nanometre wavelengths: Short wavelength lasers were to be developed using either the so-called “collisional excitation” or “recombination” schemes.

9. Demonstrated high-average power HHG and soft x-ray lasers: Several 100 kHz to MHz rep-rate driver sources (fibre lasers) were to be used for HHG. The XUV yield was to be improved to make single-event detection possible.

10. Develop ultrafast imaging with techniques adapted to soft x-ray lasers: Laserlab-Europe participants aimed at performing coherent diffraction experiments using soft x-ray lasers. The narrow bandwidth of the source should allow a better resolution than other sources to be achieved.

22 partner institutions all over Europe were working on these objectives and achieved 14 deliverables consisting of remarkable and partly groundbreaking results. These 14 deliverables can be summarized as follows:

1) OPAs for the generation of few-cycle, passively CEP-stabilized near- and mid-infrared pulses have been realized. The development and handling of such dedicated, ultrashort pulsed laser sources is a key to observe and understand the motion of electron wave packets in solids, e. g. during electronic excitation or charge transfer processes in natural and artificial light harvesting structures.

2) The activities carried out demonstrated the successful use of advanced mid-IR sources for spectroscopic analysis and strong field applications. The development of these advanced new sources and tools in the JRA context has strong potential to grant improved access opportunities to the involved partner laboratories.

3) Improved THz beams with tailored properties were demonstrated. Combination of THz emission from multiple filaments has been shown giving spectrally enhanced and circularly-polarized THz radiation. A high intensity THz source with multiple THz pulses generated from the same optical pulse with a controllable delay was implemented.

4) Multiple new laser systems have been realized that have extended the energy range of HHG (even reporting a record high output at 500 eV) or the energy per pulse at lower photon energy (e.g. 145 eV, enabling attosecond physics) and improved XUV beam quality. Also the foundation has been laid for further improvements in the future by realization of optimized laser systems for HHG, special nozzles for quasi-phase matching, and theoretical/numerical investigations into the optimum conditions for generating high energy photons at a high yield.

5) One deliverable addressed the possibility of using nanostructures to shape and influence strong field recollision and its subsequent electron or photon emission. Naturally, theoretical tools were developed and employed to describe high harmonic generation and above threshold ionization effects based on strong field approximation models but also ab-initio and in combination with finite element models. Experiments were successfully conducted at low intensities in plasmonic structures to investigate the accuracy of theoretical models, and at high intensities in plasmas and gases at higher pressures.

6) Methods for (i) the full characterization of the polarization state of high harmonic generation and (ii) for XUV-pump-XUV-probe studies of 1fs scale dynamics have been experimentally demonstrated. Towards single shot non-linear autocorrelation of attosecond pulses (i) an approach and set up has been modelled and assessed and (ii) spatially resolved two-XUV-photon ionization of He has been experimentally demonstrated. A “detector” (method and apparatus) of electron trajectory interference has been experimentally demonstrated.

7) Many INREX participants have worked to develop beamlines to deliver femto- and attosecond XUV pulses for applications in atomic/molecular and solid-state physics. These have enabled access experiments to be performed in gas-phase molecules and novel materials. Beamlines were also developed to deliver high-energy XUV pulses to target, enabling XUV-pump XUV-probe experiments. In parallel, INREX partners have been developing new techniques for generating and doing spectroscopic experiments in the UV, which will enable novel spectroscopic XUV experiments in the near future.

8) The objective of demonstrating multiphoton processes in the XUV range has been attained in several types of experiments. Though requirements of high XUV flux were drastic, the studies could use the ultra-short harmonic source and moderate density gas targets. These conditions offer a variety of multi-frequency schemes for time-resolved pump-probe studies, in particular in the gas phase, which can now be implemented by all Laserlab partners. They prepare possibly “easier” experiments of multiphoton scattering on denser solid state targets, to the expense of a larger number of scattering channels to be resolved. The remarkable creativity of nonlinear studies on the harmonic source also prepares for studies with FELs at much higher XUV flux, which certainly constitutes one of the very promising perspectives.

9) Synchrotron radiation from a permanent magnet undulator, in combination with laser wakefield accelerated electrons, has been investigated in the 30-200 nm spectral range. XUV radiation has been measured simultaneously with the electron energy spread and the correspondence between the two spectra has been established. Excellent beam transport has been established. A study of emittance development through the transport system has been undertaken, which shows that the emittance is not spoiled and remains close to 1 π mm mrad. These studies will improve access opportunities because they contribute to better characterised radiation from an undulator, as a pre-requisite for a future free-electron laser. Furthermore, new numerical studies of secondary sources will contribute to the development of new types of sources with unique characteristics.

10) Theoretical studies were successfully delivered, tackling FEL physics with simulations and the support of experiments. As could be predicted, once the tools were set in place to study the classical geometries, immediately novel solutions that made use of the additional degrees of freedom offered by the plasma medium started to be explored. This work is very promising and may lead to exciting new discoveries in plasma-based secondary sources of ultra-bright radiation.

11) The teams have investigated betatron sources in the resonant and non-resonant regimes and measured the polarisation, source size, critical frequency, divergence of the emitted X-ray radiation. Critical frequencies as high as 500 keV have been measured and a peak brilliance equivalent to a third generation synchrotron source has been measured, though the average brilliance is low because of the low repetition rate of the lasers driving the LFWA. The teams have also undertaken studies of phase contrast imaging. They have also developed a new theory of the ion channel free-electron laser.

12) The participating partners have worked on different aspects of seeding and amplification processes in plasma X-ray lasers (XRLs). One aspect was the adaptation and optimization of the seeding sources to the required properties. This was pursued at different laboratories with different tools. In collaboration with INFLPR, CNRS-LOA and CNRS-ISMO a seeded soft x-ray laser was implemented at the LASERIX facility by CNRS-LUMAT as early as 2013, employing HHG with < 50 fs laser pulses.

13) Both the XRL at MBI and the HHG source at CELIA have been commissioned as user stations. One XRL user beamline will be used for Fourier transform holography experiments in LASERLAB IV. The compact CELIA setup is also compatible with pump-probe experiments and CELIA is currently testing this possibility (collaboration F. Lépine et al., ILM Villeurbanne) as it will be very important for future experiments.

14) A lot of new developments and breakthroughs have been achieved during the Laserlab III project and collaborations have been either strengthened or created. These developments have opened new approaches that have been shared between partners and can now be used in the respective laboratories. A general trend in this work is the transfer of techniques initially developed with X-ray lasers toward high order harmonic sources. It has led to approaches that can be used both with X-ray laser or harmonic sources. These achievements clearly open new possibilities that were not accessible before the Laserlab program. In return, they will widen the range of possibilities offered by the Laserlab partners via the access program and improve the access quality.

The top highlights of the INREX research (partly overlapping with what was presented above) are:

- ICFO has set up a sub-2-cycle, CEP stable OPA source with 600 microjoule pulse energy at 1850 nm central wavelength and 1 kHz repetition rate.
- POLIMI studied the interaction of intense mid-IR pulses with molecular clusters. Carbon dioxide clusters were excited by a few-cycle mid-IR laser pulse (1.45 mm, 20 fs, 1.3 mJ) and subsequently ignited by a delayed 800-nm pulse.
- STRATH carried out two studies on production of THz radiation using a laser-plasma wakefield accelerator (LWFA). Intense single-cycle pulses with bandwidths of more than 150 THz have been generated using coherent transition radiation.

- CEA-SLIC has used photoemission spectroscopy for fully characterizing the polarization state of the high harmonic radiation from a variety of generating media (SF_6, N_2 molecules).
- FORTH, in collaboration with MPQ, has managed to measure spatially resolved two-XUV-photon ionization of He atoms, a central prerequisite towards single shot 2nd order autocorrelation.
- LLAMS has designed and partly assembled an experimental setup for HHG in gas, including focusing optics for XUV/laser pulses to excite multi-photon transitions in atomic/molecular systems.
- CLPU, in collaboration with ICFO and Imperial College, has theoretically explored new routes in HHG at high laser intensity, i.e., beyond the saturation intensity for which atoms are efficiently ionized. Detailed study of the electron dynamic outlines the contribution of “non-adiabatic trajectories” that take place in the steep turn-on of the driving laser field.
- LU-LLC has boosted the pulse energy of the HHG beam line by implementing a loose focusing geometry. The beamline now delivers attosecond pulse trains in the 17-50 eV photon energy range with pulse energy at the µJ level.
- IST deploys OSIRIS, a massive particle-in-cell code for laser-plasma interaction, which is one of the main simulation toolboxes for the plasma wakefield acceleration community. The radiation package jRad, a post-processor to OSIRIS, is now fully operational, allowing for the calculation of radiation from accelerated particles including relativistic corrections due to electron recoil in moderate radiation cooling scenarios.
- Compton radiation produced by colliding a femtosecond laser pulse and a relativistic electron beam from a laser plasma accelerator is now routinely produced at CRNS-LOA. It has in particular been used for single shot radiography in the hundred keV range.
- In collaboration with INFLPR, CNRS-LOA and CNRS-ISMO a seeded soft x-ray laser has been implemented at the LASERIX facility by CNRS-LUMAT.
- FVB-MBI developed a high repetition rate plasma based soft X-ray laser emitting coherent light in the extreme ultraviolet region at 18.9 nm using a molybdenum target.

1.3.3.3.3 Potential impact

All these developments will be extremely important for the proliferation of attosecond / THz / X-ray physics, respectively, in Europe. Especially in attosecond physics, Europe has – not least due to Laserlab-Europe – a leading role in the world, which was kept and strengthened by the scientific efforts in INREX.

Extension of attosecond physics to new systems (solids, layered systems, more complicated molecular systems), development of new techniques in THz physics, increasing flux and photon energy of various X-ray sources opens up new fields in physics that were out of reach so far.

The infrastructure set up in this JRA offers state-of-the-art tools for scientists in many disciplines. New users who did not have the possibility to access sources like the ones that have been developed in INREX may now have the possibility to perform experiments at new dimensions and may consider breaking borders in their thinking.

Last but not least, the laser community in Europe has grown together even more. The new members from Eastern Europe have been able to integrate into the community by performing collaborative research in the framework of INREX and by using the networking efforts of INREX, be it in joint research at various facilities, be it at the scientific meetings that were organized several times at different places.

1.3.3.4 WP33 – European Research Objectives on Lasers for Industry, Technology and Energy (EURO-LITE)

1.3.3.4.1 Executive Summary

European Research Objectives on Lasers for Industry, Technology and Energy (EURO-LITE) involved 18 partners from leading laser physics research laboratories. This Joint Research Activity focussed on several key laser physics bottlenecks, all crucial for most of the research laser systems operating or being built throughout Europe. Improving the temporal contrast was the subject of Objective 1, whereas Objective 2 was dedicated to laser amplification studies on gain medium, laser induced damage, pump source and thermal management. Finally, objective 3 focussed on attosecond laser technology. Description of the main scientific results and the wide impact of these activities are detailed in the following two dedicated subsections. EURO-LITE partners met on five occasions at a frequency of about 10 to 11 months during the present Laserlab-Europe contract. Besides achieving 14 tasks, completing 30 deliverables in due time, publishing numerous scientific articles, patenting several innovative concepts/apparatus, the partners succeeded in performing real joint research activities through multilateral collaborations. These activities ranged from personnel, materials/devices or data exchanges, know-how transfer, expertise sharing, joint experiments, collective publications, collaborative devices conception/implementation and even common proposals for future joint work.

1.3.3.4.2 Description of the main S&T results

At **CEA-CESTA**, various frequency-doubling schemes were numerically simulated. A reference Maxwell code is now fully operational and has been qualitatively validated with negative uniaxial crystals such as KDP and BBO. An experimental technique to obtain such parameters was proposed. The second code used was MIRÒ software, which is routinely used to model and optimize the performance of complex high-energy laser chains. It is based on a split-step numerical algorithm solving the non-linear Schrödinger equation in free space and in a large number of optical components, including laser and non-linear crystals. MIRÒ was used to model the most advanced and promising experimental configurations. Comprehensive experimental setups have been exactly modelled, including pulse-front tilting in prism pairs, broadband relay imaging and transport of angularly-dispersed beams, non-collinear interaction in uniaxial and biaxial crystals, pulse stretching and compression. Beam, pulse and front-tilt shaping were successfully modelled and quantitatively validated. At **GSI**-PHELIX, a new ultrahigh contrast frontend system was developed and implemented during this program, together with HIJ and GoLP. As a result, experimentalists can now select pulse contrast levels between 10^6 and more than 10^{10}, if necessary on a daily basis. This improves significantly the range of experiments which can be performed with the PHELIX laser system because targets with thicknesses below 1 µm would not withstand the intensity of a lower-contrast pre-pulse. Additionally, an Nd:glass preamplifier scheme with the compensation of thermally induced birefringence has been developed and will be implemented soon. This system will enable a higher shot repetition rate at the few-J level which is highly desirable for preparatory experiments which, in turn, allow for more efficient usage of the full-aperture system because diagnostics can be tested and pre-aligned without the use of 90 min repetition rate shots. At **USZ** different angular dispersion measurement methods were studied. A slight misalignment of CPA systems can lead unwanted angular dispersion, which results spatiotemporal aberrations in ultrashort pulses. Therefore it is necessary to measure and correct any residual angular dispersion in the CPA chains. Applicability and accuracy of three different techniques were compared in our work. In next two years, we focused on the relative CEP shift detection in Ti:Sa amplifiers, which are essential parts of intense ultrashort pulse laser systems. The relative CEP shift defines the accuracy of phase related experiments (e.g. attosecond pulse generation). The measurement and simulation of the CEP changes introduced by the Ti:Sa amplifiers are thus significantly important. Based on experimental and numerical results, it was concluded that the main sources of the CEP changes during amplification are the heat load in the gain medium caused by the pump pulses, and the mechanical vibrations of the optical components. **IST** was involved in the development of an ultra-broadband optical parametric chirped pulse amplification (OPCPA) laser system. They have successfully designed and installed an OPCPA generating pulses with a duration below 20 fs and multi-mJ energy at 1 Hz repetition rate. The design is based on (i) full-diode-pumping, (ii) nonlinear amplification in the crystal yttrium calcium oxyborate and (iii) optical synchronization between pump and signal. The pump laser is based on CPA and consists of a 3 mJ, 10 Hz,

$Yb:CaF_2$ regenerative amplifier and 100 mJ, 1 Hz, eight passes Yb:YAG amplifier at 1032 nm. A fraction of the amplified pump is used to generate white light continuum in bulk media, which is mixed with the second harmonic of the remaining pump in two YCOB crystals. This medium was studied in detail, numerically and experimentally, in order to optimize the phase matching angles. The amplified pulses exhibit a bandwidth corresponding to a transform limited pulse duration of 7 fs. IST also tested and characterized the performance and spectral transmission of the stretching and compression stages, consisting of an SF11 block (stretcher), and a transmission grating + SF11 prism pair (compressor).

FVB-MBI investigated active and passive methods for beam pointing stabilization at a thin-disk laser system. By monitoring the position of the amplified beam and re-adjusting it with the help of a motorized mirror within the amplifier the pointing as well as the pulse energy could be stabilized significantly. The stability of the output pulse energy behind the regenerative amplifier as well as the multi-pass amplifier was better than 0.3% (rms). This active stabilization compensates for the thermal drift during the day on a timescale of minutes. Fluctuations on a shorter timescale cannot be compensated by this method. By re-designing the thin-disk pump heads to be gas-tight fluctuations in the beam profile due to air turbulences in the beam pass could be reduced. A further positive influence of Helium that should replace the air within the pump head could not be observed. Due to the long beam pass in thin-disk amplifiers it is very important to guide the beam in tubes to minimize the chance of air turbulences. Regarding task 2, FVB-MBI experimental tests of the cross-correlator for 532 nm have shown its functionality. Parametric amplification used in the cross-correlator is very sensitive to the quality of the laser beam. Thus, a laser signal of a few picosecond duration with a good phase front is required to reach the optimum performance. Scatter of radiation on some elements of the optical setup of the signal beam that limited the dynamic range of the first prototype was fixed in the second version of the device.

Laser-induced-damage threshold (LIDT) measurement capabilities were extended at **VULRC** and GSI for demanding testing of laser parts under extreme environmental conditions (both in vacuum and low temperatures). LIDT testing was conducted on most critical coated and uncoated laser components at various pulse duration (fs-ns) and wavelength irradiations (UV-IR) and provided useful power assurance levels for the community of laser developers. Also, a CEP-stabilized few cycle OPCPA system pumped by fs Yb:KGW and ps Nd:YAG lasers was developed. The front end produces passively CEP-stabilized pulses with spectrum corresponding to transform limited pulses of ~ 5 fs and CEP jitter is below 120 mrad. In the test experiments on pulse amplification in ps NOPA stages and their compression the output pulse compression down to ~ 8 fs was demonstrated. After completion in 2016 the system will produce sub-10 fs pulses of ~ 1 TW peak power at repetition rate of 1 kHz. With a newly developed experimental equipment for the measurement of optical damage threshold on laser materials and other coated optical elements highly laser pulse resistant coatings on different laser materials could be selected at **GSI-HIJ**. This helped to improve the coatings on these materials that are applied in several large scale laser facilities of cooperating partners. Moreover, new laser glasses that will be used at the POLARIS laser at the Helmholtz-Institute Jena were tested. It was found that damage thresholds are much higher than that of the glass applied so far. This will help to improve this particular facility and to finally provide a better performance for the users. In terms of future developments anti-reflection coated sapphire was found to be applicable as an optical element for heat removal in cryogenically cooled laser heads. For such a laser head a patent was applied, which will be industry exploited with applications in material processing and science. Further, in order to prepare for CEP-correction on the fly, a scheme was developed and patented to investigate dispersion of different materials and its controllability. This was done by means of few-cycle pulses and two stereoscopic ATI-spectrometers.

The **INFLPR** research aimed at the realization of ceramic-host materials doped with various rare earth ions, in principal suitable as gain media with large fluorescence bands. Nd:YAG ceramics with good transparency were realized by solid-state reaction method and using vacuum sintering and annealing processes that were performed with the help of the collaborators from Institute of Science and Technology for Ceramics (CNR-ISTEC) in Italy. A new ceramic material, 1.0-at.% Sm^{3+}:YSAG, was obtained by the same method. High resolution spectroscopic investigations (emission and absorption spectra) were performed. A disordered Yb:CLNGG laser crystal was growth and laser emission was obtained under quasi-continuous wave pumping with fiber-coupled diode lasers. In addition, waveguides were realized in Nd:YAG ceramic by direct writing with a femtosecond-laser beam and efficient laser emission at 1.06 μm and 1.3 μm was achieved from such waveguides. The **CNR** partner studied two different processes for the production of Yb:YAG transparent ceramics samples with a longitudinal doping gradient (aimed at optimizing the thermal and ASE management in high power/high rep rate laser systems). A variety of Yb:YAG samples with diameter around 1-2 cm, thickness around 3-4 mm and different longitudinal doping structures were produced. Their optical characterization under different thermal loads using different techniques was also carried out. The so-called Tape Casting method showed a few advantages over the conventional Pressing of Spray Dried Powders method, in terms, for instance, of a reduced density of large (~tens of microns) defects, improved transmission, smaller thickness of the diffusion region between layers with different doping level.

At **STFC-CLF**, the DiPOLE laser system was designed to run at 10J at 10Hz. The amplifier uses cryo-cooling of the amplifier medium. The output energy achieved was 10.8 J at 10 Hz, with a pump pulse of 1.2 ms duration, equivalent to pump energy of 48 J, giving an optical to optical conversation efficiency of 22.5%. Long term performance was achieved by reducing the fluence to 2 J/cm^2, with an output of 7 J at 10Hz over 50 hours (this was achieved in runs of 3-5 hours at a time). Energy of the system for a 1.8 million shots with an 0.85% rms overall energy. The temporal pulse width can be controlled with a 200 ps resolution, by use of an EOM and an AWG. A range of temporal pulse widths were experimented with an output pulse of 2 – 10 ns. A 2 ns pulse widths the output energy was reduced to 4.5 J, to reduce the probability of damage to the optics and gain medium. The **CNRS-LULI** team explored Cr^{4+}/Yb^{3+}:YAG co-sintered ceramic disks and obtained gain as high as 20 in a single pass when operating the amplifier below 90K. More than 8.5 Joules could then be achieved by activating the complete chain with 2 passes in low temperature and room temperature amplifiers**.** The innovative concept of low temperature cooling through a thin layer of static gas was experimentally demonstrated. **CNRS-LOA** worked on the modelling and design of an amplifier module based on ceramic material, and the team was able to perform experiments on an innovative design for which the pumping is made by passing the pump beams through the coolant. This amplifier module combines the use of Yb:YAG ceramics with 940 nm laser diodes for pumping in order to enjoy better performance stability over the long term. Despite critical conditions, amplification of ns and fs pulses in single pass with gains up to 3.2 was obtained. Double pass has also been proved to be possible and to enable to double the gain. Different single and hybrid ceramics with different width and doping level have been tested and an optimum has been found. Thanks to LOA specific mount, a significant improvement in performances (gain saturation in particular) compared to a conventional cooling, without the use of cryogenic cooling, was observed. In addition, control of thermal deformations of the wave front looks promising.

CNRS-CELIA demonstrated the great advantage of using diffraction limited fibre pump lasers emitting at 976 nm to pump Yb-doped laser materials. More than the actual average power, the brightness is the parameter of interest for efficient optical pumping. The group demonstrated so far a brightness of 3450 $MW.cm^{-2}.sr^{-1}$ with a microstructured rod-type fiber (40 W) and 2773 $MW.cm^{-2}.sr^{-1}$ with a flexible fiber (32 W). Increased power/brightness up to 100 W will require beam combining. They used this pump in a booster amplifier architecture and demonstrated single pass gain of up to 5.7 in a long $Yb:CaF_2$ crystal with a train of sub 70 fs pulses reaching an average power of 16.5 W. CELIA also reported on exceptional performances of a Kerr-lens mode-lock fs oscillator. In fact, thanks to the high brightness longitudinal pumping, transform-limited pulses of 32 fs have been recorded which sets a new record for Yb-doped fs oscillators. Moreover, this technology allows to generate sub 50 fs with several W average power.

FORTH developed a method for the online shot-to-shot measurement of the absolute CEP value of many cycle high peak power laser pulses, a software for the tagging of measured spectra with the CEP, a novel collinear polarization gating method and device and integration of it in a ~18 fs, 400 mJ Ti:Sapphire laser system, for an estimated output of ~10 mJ in a 3.5fs "linear" polarization gate. It also developed an energetic coherent XUV source based on laser plasma harmonic emission and demonstrated non-linear processes and applications in the XUV spectral region. It finalized the upgrade of the attosecond S&T lab. With laser specs of 400 mJ, 18 fs @ 10Hz. New loose geometry coherent attosecond XUV source was constructed. Indicative spec are ~10^{12} photons/pulse at 25 eV photon energy. **ICFO** developed a sub-2-cycle 1 kHz system at 1850 nm with 0.5 mJ pulse energy. Unprecedented sub-100-mrad CEP stability over 72 hours was achieved along with record HHG spectra covering 200 eV to 550 eV; the entire water window soft-X-ray range is thus spanned for a single shot. This first source of attosecond soft X-rays, now available for access within

Laserlab Europe, was validated with the first ever demonstration of near edge soft-X-ray fine structure spectroscopy (NEXAFS) at the carbon K-shell edge in a solid target. **LENS** developed spectroscopic tools in combination with Mid-IR frequency-comb sources. The "intracavity quartz-enhanced photoacoustic spectroscopy" technique was developed and employed for trace-gas detection in the mid-IR. LENS showed that the recently introduced "saturated- absorption cavity ring-down" technique enhances resolution (up to 3 orders of magnitude) and sensitivity (~20 times) with respect to conventional cavity ring-down spectroscopy. Finally, using the home made mid-IR comb based on intra-cavity DFG process in a Ti:sapphire laser for broadband direct comb spectroscopy, LENS achieved absolute frequency measurements with wide tunability (4.2 - 5.0 μm) and high coherence (2.0 kHz linewidth). Vernier spectroscopy of CO2 absorption in ambient air was demonstrated with individually-resolved comb teeth. At **MPQ-MPG**, a new electric field measurement technique was provided to researcher working with infrared radiation (electro-optic sampling), allowing for simple and direct access to the temporal variation of coherent laser fields in this important spectral range. **CEA-SLIC** investigated the potential of using the Electro Optic effect in a crystal to control the CEP of the laser drivers. Using a bulk Electro-Optic crystal phase shifter associated and a fully analogical loop developed by SLIC, CUSBO and the Amplitude-Technologies company, the CEP remaining noise of a 20 W, 10 kHz, 25 fs Ti:sapphire laser was reduced down to 320 mrad shot-to-shot and the correction bandwidth was significantly increased. SLIC also developed a CEP phase shifter that uses two Electro-Optic prisms in a configuration close to a prism compressor. Experiments carried out with RTP prisms demonstrated that this set-up can be used either to shift the CEP without modifying the group delay (isochronous CEP shifter) or to generate group delay with constant CEP (Pure Group Delay generator).

1.3.3.4.3 Potential impact

Objective 1 & 2: CEA-CESTA in-depth understanding of second harmonic generation taking into account the variation of the non-linear tensor versus wavelength is an important step towards frequency doubling of ultra-short pulses. The results of the ultrahigh-contrast project at PHELIX (**GSI**) show that it is possible to provide this option on a long-term basis for user experiments. The fact that the contrast level has been verified with full-system shots underlines the reliability of the approach. Especially for particle acceleration experiments using mass-limited targets, this development has been a mandatory milestone. The results of **USZ** work impacts most high intensity, few-cycle laser systems. It can affect the laser system developers and laser industry as well, and potentially trigger new solutions for better CEP stabilization of few-cycle pulses. All scientific experiments using these type of light sources (e.g. attosecond sciences, high harmonic generation, particle acceleration, medical applications, etc.) can benefit from the improvement of better spatiotemporal and phase properties of ultrashort pulses. These improved laser parameters can broaden the user community and create new collaborations in the future. The **IST** work leading to the development of an ultrashort, ultrabroadband laser has led to the continuation or establishment of the following collaborations: PHELIX group (GSI, Germany) and IOQ (FSU, Germany) for short pulse OPCPA and diode-pumped amplifiers; CLF (STFC, UK) for characterization of ultrashort lasers; ICFO (Spain) for preliminary work on development of mid-infrared OPCPA lasers. The new laser will add to the laser capability of the L2I facility at IST, which is being prepared for access in the scope of the Portuguese roadmap of research infrastructures. **FVB-MBI** active stabilization can be adapted to other laser systems. It is especially interesting for larger systems where a proper installation to guarantee a high degree of temperature stability is not easy to implement. It is used to compensate for thermal drifts during the day and is now available for experiments. **VULRC**, together with CNR – ISTC (Italy), LULI (France) but also with partners from Israel, UK and Austria, established a consortium for the development of advanced laser ceramic material development and applied for a new joint European project. The new improved research infrastructure (EXTENDED CAPABILITIES) opens access opportunities for science and industry projects and namely environmental LIDT testing at VU. A new cooperation of VULRC with the European space agency (ESA) and Laser Zentrum Hannover e.V. allows Round-Robin experiments in vacuum testing. The OPCPA system developed at VULRC is a significant improvement of the laser infrastructure at Vilnius University for research in the field of high intensity laser physics, extreme nonlinear optics, attosecond science and will open the new opportunities for transnational access for external scientists. The concept and general design of OPCPA systems developed at VULRC is used for building the SYLOS beamline of the ELI-ALPS facility in Szeged, Hungary. The research performed at **INFLPR** was done for the first time in Romania and basically it increased our area of competences in the field of laser physics. Nd:YAG transparent ceramics were obtained, showing the possibility to realize large-size such media in our country. The disordered Yb:CLNGG crystal is a good candidate for mode-locking operation, while YSAG ceramic could be used as laser medium as well as in phosphor applications. Realization of femtosecond-laser beam written waveguides in Nd:YAG showed the potential of such devices to build efficient integrated laser sources (that are pumped by fiber-coupled diode lasers with applications in optoelectronics. The work carried out by the **CNR** was mainly aimed at the development of production processes for laser grade Yb:YAG transparent ceramic samples with a few cm diameter with longitudinal doping gradient; the ultimate goal was their use as active media in high power and high rep rate laser systems, with the chance of a better thermal and ASE management over media with a uniform longitudinal doping structure. The possibility of producing samples with up to 2 cm diameter and a few mm thickness and made up by up to 5 layers with different Yb doping level was demonstrated. These kind of samples may impact the design of high rep rate laser systems, in particular at large scale research infrastructures. **CNRS-**LULI low temperature cooling through a thin layer of static gas is a patented innovative approach. Contact have been taken with laser companies to licence it since the validity of the concept is now demonstrated. Scientific results on laser-induced damage testing at **GSI-HIJ** are readily applicable by industry to produce optical elements and laser systems with higher performance and reliability. It also revealed that newly developed materials are promising for using them in high peak power lasers with strong scientific impact as well as potential application in industrial lasers for material processing. The adoption of these materials with improved coatings in user facilities helped to improve their performance. With the therefore provided higher peak powers of some of these lasers at the partner’s facilities new scientific research could be offered. Additionally newly explored materials are able to improve the laser facilities by higher repetition rate cryogenically-cooled diode-pumped laser systems as pump lasers for parametric amplifiers or direct amplification of femtosecond laser pulses. Industry will benefit here as a supplier of laser technology also. Research in cryo-cooling amplifiers using Yb:YAG as the gain medium at **STFC-CLF** increases the knowledge for high repetition rate amplifiers. This impact on the laser science community in the field to design high energy lasers for pumping OPCPA and the drive to fusion lasers. This also proves the next step to building 100J/1kJ amplifier systems. These systems can be used in industry for laser peening and other industrial processes.

Although **CNRS-LOA** worked mainly on feasibility studies, its research project presents an original amplifier module concept. Its purpose is to achieve a significant advance in performance and compactness of high repetition rate, high average power amplifiers which are rather limited for the moment. As such, it has great potential because the realization of compact sources of high average power and high peak power would allow considering very interesting progress in the generation of secondary radiations such as THz waves and filamentation, for example. In addition, the potential in terms of nano-machining are also significant, and further applications become possible, for example cleaning or etching substrates and thin film deposition by evaporation.

The activity carried out within the **Objective 3** of EUROLITE also had significant impact on the European scientific community. Firstly, the activity led to new synergy with the synchrotron facility along with potential industrial impact and improved access opportunities. **ICFO** developed the first few-cycle and CEP stable long wavelength driver for attosecond generation in the water window regime, thus achieving the first table top source of fully coherent soft X-rays. This source was also proven to yield isolated attosecond pulses at the fundamental absorption edge of carbon at 300 eV. The scientific and industrial impact of this new table top source might be very high as it can supplement large scale facility light sources now on a table top and with access for chemists, physicists and material scientists alike. Despite being very new, the parameters of this source have already led to request for beam time from the synchrotron user community as well as from beamline scientists. The capabilities of the ICFO source are highlighted in the ALBA CELLS newsletter which is being distributed across the synchrotron user community. New collaborations were formed with the synchrotron user community at ALBA in Barcelona, Soleil in Paris and Bessy in Berlin. High repetition rate harmonic generation, developed at **CELIA** is also scientifically important since it opens the possibility to perform coincidence experiments that are routinely performed on synchrotrons without temporal resolution. With this kind of XUV source, temporal resolution is granted. This development might also have a significant impact for industry because the tight focussing XUV source is very compact and compatible with the use of small industrial lasers. This compact VUV source may lead to new industrial product if the market expands.

On addition, several developments are of interest for a large community of researchers involved in laser science. In many cases, these developments are already offered to external users of the facility which developed them. Some might lead to industrial products. These developments are described in detail in the report D33-30 and only a few examples are given here.

For instance, **LOA** developed an innovative, robust and unique plasma mirror-based light and particles source for ultrafast applications that is available to external users and whose several components are now commercialized by LOA spin-off company SourceLAB- France. The development work at LOA induced new collaborations with University of Hannover and Max Born Institute (MBI) in Berlin. In addition, LOA developed a new simple in-situ technique to probe plasma mirror expansion velocity, which is a key parameter in the fundamental study of ultra-high intensity laser-solid interactions and is therefore of interest for a large community.

CEP stabilisation and measurement is essential for the production and use of isolated attosecond pulses. **CEA-SLIC** investigated the potential of Electro-optic CEP shifters. This work was mostly carried out for scientific objectives but had also industrial impact since this technics was recently co-patented by the CEA and the Amplitude-Technologies company (before the beginning of the present Laserlab contract). SLIC confirmed that Electro-optic CEP shifters can be efficiently used to CEP stabilize ultrafast lasers. Furthermore, SLIC achieved for the first time isochronous CEP stabilization; this was made possible thanks to a particular arrangement of two Electro-optic prisms and might be of importance for pump-probe experiments with CEP pulses produced by 2 different lasers. Electro-optic CEP shifters will be implemented on the new FAB1-10 laser that is presently commissioned at SLIC and will be open for external access from 2017 within the Transnational Access Programme of Laserlab-Europe. **GSI-HIJ** continued to implement the ATI phasemeter scheme for CEP measurement and achieved single-shot CEP measurement of a high intensity (40 TW) low repetition rate (10 Hz) laser system. This is also of large interest for the laser scientific community since the investigation of CEP effects in experiments, e.g. surface high harmonic generation, at high power laser systems requires a characterization setup witch can be operated with low repetition rates (usual feedback loops which are used to stabilize the CEP are not applicable under these conditions). Also concerning the metrology of ultrafast pulses, **MPQ** provided a new electric field measurement technique to researchers working with infrared radiation (electro-optic sampling), allowing for simple and direct access to the temporal variation of coherent laser fields in this important spectral range.

High energy post compression, developed at **CELIA**, is also important for science since it gives the possibility to use ultrashort few-cycle pulses at energies above the 1 mJ level, while before the pulse energy was limited below. It promises to increase the attosecond pulse energy and provides a way to perform single shot experiments with high flux attosecond pulses.

FORTH researches focussed on the development and operational improvement of energetic coherent XUV attosecond radiation sources and time domain spectroscopic techniques and devices for novel attosecond pulse metrology and novel 1fs to attosecond scale XUV-pump-XUV-probe studies. As such the research at FORTH carried *Impact on science* as it opens up a new scientific era of ultrafast dynamics based on attosecond XUV-pump-XUV-probe measurements. It also had *impact on the scientific community* as it triggered new collaborations with other communities that can use related techniques e.g. the XUV FEL communities. It further facilitates the collaboration with new up-coming user facilities (e.g. the ELI project) with which co-operation has been established. It had further *impact on the user community* as it advances the available infrastructures and thus improves access within Laserlab-Europe. Moreover, the results are relevant also for new European user research infrastructures under implementation (e.g. the ELI project), which in part is based on the methods developed in the present project.

Finally, **LENS** developed advanced coherent sources for ultra-sensitive detection and monitoring of molecules of atmospheric and astrophysical interest in the molecular fingerprint region (3-12 μm). The set-ups are compact, capable of operating at room temperature, easily tunable and intense. These new laser sources and associated spectroscopic techniques will have an important impact both in the fundamental research field (e.g. in the search for parity-violating forbidden transitions) and in the applicative domain, with the development of precise and sensitive detectors for trace gases that may surpass the performances and the availability of current state-of-the-art techniques (e.g. optical vs. mass spectrometry radiocarbon dating, hazardous gas detection, etc.). These advanced experimental setups are now available in the LENS laboratory and will further improve its attractiveness for the scientific user community.

1.4 Potential impact and main dissemination activities and exploitation of results

1.4.1 Potential impact including the socio-economic impact and the wider societal implications of the project

a) Structuring effect on the quality and operation of European laser RIs, and on the capability to attack scientific problems beyond the national scale:

Laserlab-Europe has understoond itself as the central place in Europe where new developments in laser research are tackled in a flexible and co-ordinated fashion beyond the potential of a national scale. This is a mission that is crucial for maintaining Europe's leading role, but can neither be fulfilled by the user community (for reasons of scale), nor by the ESFRI projects with their own very specific missions. Notwithstanding, Laserlab-Europe has reached out to both sides: to the user community through its high-quality Transnational Access activities, and to ELI through common research objectives, best-practice management development, and development of human resources at the European level. In addition, it has been particularly open to new scientific developments not covered by existing installations, to the contact with industry and, in particular, to the contact with new communities, both scientifically and geographically.

How the Consortium has filled this position is best illustrated by the choice of the four Joint Research Activities (JRAs), their objectives and the relative weight which was given to them within the project. In summary, they arose from combining the above mission with the result of a strategic foresight process, leading to the following conclusions:

- Short temporal and nano-scopic spatial events are at the frontiers of science, requiring ultra-short radiation pulses tunable from THz to X-rays.
- High-power and high-energy lasers are frequently the key to new science and innovation, but only if low repetition rates, low average powers, and low energy efficiency can be overcome.
- Laser acceleration has a huge potential as a source of energetic particles, and for applications of general relevance (e.g., material sciences and medicine) and future accelerators.
- Laser tools and techniques are flourishing in very active, autonomous and sophisticated applications outside physics, especially in biology and biomedicine.

The research and developments within the JRA BIOPTICHAL are of high relevance to modern biology and medicine. The novel technological and methodological developments pursued by this JRA were effectively carried out through an extensive cooperative work, exchange of knowledge, and dissemination of the results between the participants. The user basis was extended outside the borders of the consortium, especially towards the biologist and medical doctor communities, through involvement of associate medical partners and European medical societies and dissemination of the results in biological and medical conferences. The activities at the collaborating infrastructures within this JRA were spread also to other members of Laserlab-Europe. As research in the field is a world-wide activity, it is extremely important that European researchers are at the forefront in this highly competitive field.

The objectives pursued by BIOPTICHAL were aimed at creating substantial technical developments for research and diagnostic tools. Connections with industries allow the exploitation of such developments and create new opportunities for research and jobs. Connections with hospitals and clinics has allowed, and will even more in the future, the test of the diagnostic and therapeutic tools developed through this JRA directly on patients. Moreover, a network formed by associated groups, working on specific topics, and hospitals has boosted the development of specific deliverables and brought additional value to the project.

Several patents have been registered for technological developments resulting from research in the context of this JRA, and spin-off companies of Laserlab-Europe partners and other industrial partners are exploiting the results commercially through licensing. A number of new jobs have been created in spin-off companies that exploit the results of the research in relation to the JRA BIOPTICHAL.

Europe maintains a strong and leading position in the field of secondary sources driven by intense lasers. Some of the results of the JRA CHARPAC are at the core of the most important advances in this field. CHARPAC has contributed to maintain the European leadership and has served as an important pool of resources and a forum for the key teams in the field.

The scientific impact has been tremendous, not only in terms of publications but also in terms of training of students and post-docs. This is critical for the future of the field in Europe given the large number of facilities in Europe already deployed or soon to be deployed that will require a significant amount of trained personnel. Examples of these facilities are, for instance, APOLLON (France) and the three ELI pillars (Czech Republic, Hungary, Romania).

Research of high-intensity laser-plasma interactions is decidedly multi-disciplinary. PhD students and young researchers have to master many aspects of physics and engineering in order to succeed. For example, all students involved in the activities of CHARPAC learn the key aspects of laser-plasma interactions and in many cases they operate and maintain a multi-terawatt laser system. Therefore, they get considerable training in advanced optics and laser technology and several of the PhD students work in the photonics industry (i.e. optics and laser development) after they graduate. Through hands-on experience with energetic charged particle beams, they also receive practical training in nuclear- and accelerator physics and instrumentation, and several graduated PhD students currently work at advanced accelerator facilities.

The CHARPAC JRA played a vital role in creating new and in consolidating existing transnational scientific collaborations, both with partners within and outside the Laserlab-Europe consortium. The collaborations have contributed to the development of new instrumentation and diagnostics for the different user communities and facilities, opening up new research opportunities at future laser facilities, e.g. at APOLLON and ELBE. Moreover, the teams involved in CHARPAC have also pooled their resources to participate in large EU projects, e.g. EUPRAXIA, and CHARPAC did play an important role in integration and as forum for the scientific community working in these topics.

The results achieved within CHARPAC are not only important for the scientific community but also for industrial applications, e.g. for medical applications of laser plasma accelerators that will be explored in the future. A recently created company offering systems for laser facilities will benefit from the advances in relation to CHARPAC through a tech-transfer agreement with LULI, allowing for commercial exploitation of target and diagnostic systems.

These brief examples illustrate the multilateral and collaborative efforts within CHARPAC, not only in scientific terms, with many joint publications, but also as a leverage to more ambitious and fruitful collaborations that have and will continue to have impact in the main scientific and technological developments in the field of laser-plasma accelerators. CHARPAC has also contributed to the training of many PhD students and post-docs that are now involved in many exciting laser infrastructures in Europe and in the photonics industry. Furthermore, the optimization on the sources has clearly paved the way for the applications that will be pursued in future and ongoing pan-European projects that will address the challenges associated with applications.

The developments within the JRA INREX will be extremely important for the proliferation of attosecond, THz and X-ray physics in Europe. Especially in attosecond physics, Europe has – not least due to Laserlab-Europe – a leading role in the world which could be kept and strengthened by the scientific efforts in INREX.

Extension of attosecond physics to new systems (solids, layered systems, more complicated molecular systems), development of new techniques in THz physics, increasing flux and photon energy of various X-ray sources opens up new fields in physics that were out of reach so far. The infrastructure set up in this JRA offers state-of-the-art tools for scientists in many disciplines. The development of advanced new sources and tools in the JRA context has strong potential to grant improved access opportunities at the involved partner laboratories, and new users who did not have the possibility to access sources like the ones that have been developed in INREX may now have the possibility to perform experiments at new dimensions and may consider breaking borders in their thinking.

Last but not least, the laser community in Europe has grown together even more. The new members from Eastern Europe have been able to integrate into the community by performing collaborative research in the framework of INREX and by using the networking efforts of INREX, be it in joint research at various facilities, be it at the scientific meetings that were organized several times at different places.

For several research outcomes in the framework of the JRA INREX, patent applications have been filed and commercial exploitation of the results through licensing is pursued.

The JRA EURO-LITE focussed on several key laser physics bottlenecks crucial for most of the research laser systems operating or being built throughout Europe. The joint work resulted in a very rich output not only in terms of scientific articles but also in in patenting several innovative concepts and devices. The results are the basis for establishing connections and cooperation with industries for commercial exploitation.

For example, the improvement of spatiotemporal and phase properties of ultrashort pulses at USZ will trigger new solutions for better CEP stabilization of few-cycle pulses to be developed by laser system developers and laser industry. Active stabilisation techniques developed at FVB-MBI can be adapted to other laser systems. The Laserlab partners VULRC and LULI together with partners from Italy, Israel, UK and Austria established a consortium for the development of advanced laser ceramic material. Scientific results on laser-induced damage testing at GSI-HIJ are readily applicable by industry to produce optical elements and laser systems with higher performance and reliability. Newly developed materials are promising for using them in high peak power lasers with strong scientific impact as well as potential applications in industrial lasers for material processing. Research in cryo-cooling amplifiers using Yb:YAG as the gain medium at STFC-CLF increases the knowledge for high repetition rate amplifiers, which proves the next step to building 100J/1kJ amplifier systems. These systems can be used in industry for laser peening and other industrial processes.

Many new developments and techniques feed back into new options for user experiments, e.g. the ultrahigh-contrast project at GSI-PHELIX, electro-optic CEP shifters on the new FAB1-10 laser that is presently commissioned at SLIC, advanced coherent sources for ultra-sensitive detection and monitoring of molecules of atmospheric and astrophysical interest in the molecular fingerprint region (3-12 μm) at LENS, and an OPCPA system for research in the field of high intensity laser physics, extreme nonlinear optics and attosecond science developed at VULRC. The concept and general design of this OPCPA system is used for building the SYLOS beamline of the ELI-ALPS facility in Szeged, Hungary. LOA developed an innovative, robust and unique plasma mirror-based light and particles sources for ultrafast applications that is available to external users and whose several components are now commercialized by LOA spin-off company SourceLAB- France. The collaborative work leading to the development of an ultrashort, ultrabroadband laser will enhance the laser capability of the L2I facility at IST, which is being prepared for access in the scope of the Portuguese roadmap of research infrastructures.

The EURO-LITE activity also led to new synergies with the synchrotron radiation community along with potential industrial impact and improved access opportunities. For example, ICFO developed the first few-cycle and CEP stable long wavelength driver for attosecond generation in the water window regime, thus achieving the first table top source of fully coherent soft X-rays. The scientific and industrial impact of this new table top source might be very high as it can supplement large-scale facility light sources now on a table top and with access for chemists, physicists and material scientists alike. The parameters of this source have already led to request for beam time from the synchrotron user community as well as from beamline scientists. High repetition rate harmonic generation, developed at CELIA also opens up the possibility to perform coincidence experiments that are routinely performed on synchrotrons without temporal resolution. Research at FORTH focussed on the development and operational improvement of energetic coherent XUV attosecond radiation sources and time domain spectroscopic techniques and devices for novel attosecond pulse metrology and novel 1fs to attosecond scale XUV-pump-XUV-probe studies. The research triggered new collaborations with other communities that can use related techniques e.g. the XUV FEL communities, and facilitates the collaboration with new up-coming user facilities (e.g. the ELI project).

b) Impact of highly co-oordinated Access implementation on the RI landscape and the scientific User community:

For the laser community Transnational Access is the way to perform the top few percent of experiments which can only be done at truly unique facilities, giving the User community the decisive advantage in the global competition. Laserlab-Europe has developed its own policy with the goal of optimizing the use of European laser facilities and the scientific quality of User projects through the implementation of a highly co-ordinated Transnational Access plan, containing the following main elements:

- Scientific excellence of User projects through high-level *external evaluation, common to all infrastructures,*
- "*Dynamic Transnational Access budget allocation*", introducing a User-driven competitive element in consortium-wide access offers,
- *Central organisation of the application procedure*, monitoring of project scheduling and controlling the overall quality of the Transnational Access activity by a dedicated Board,
- *User involvement and User feedback*, e.g. through dedicated User meetings and User questionnaire,
- *Constant renewal of Transnational Access offers* not only through internal competition and User-driven Access allocation, but also through periodic top-down review of the Transnational Access portfolio and competitive Calls for Transnational Access opportunities (e.g. leading to new Transnational Access facilities in Horizon 2020).

The impact concerns both research infrastructures (internal impact) and the scientific User community (external impact). It consists in

- High flexibility in reacting to fluctuations in the User demand and progress of state-of-the-art, while maintaining the objectives of the total Transnational Access offer of the Consortium as a whole (dynamic Access),
- Maintaining high standards and technical and scientific complementarities in the Transnational Access offers through internal competition between host facilities and periodic renewal of the Transnational Access portfolio,
- Maintaining highest scientific standards, objectivity and neutrality in the User proposal selection process by using a unified, consortium-wide and fully external Selection Panel of highest scientific reputation,
- Providing high level training through contact with the best experimental groups and the use of top class equipment,
- Helping to maintain the internationally leading position of the European User community in cutting-edge laser research.

The Laserlab Transnational Access activity provided many opportunities to initiate new collaborations between the host institutions and researchers from all over Europe, and it has proven to be beneficial to science of both the host institution and the home institution of the visitor. It has been a win-win program and has been able to sustain the leading role of EU laser research in a global perspective by producing unsurpassed scientific results in a multitude of research fields ranging from life sciences, biochemistry, chemistry to applied and high energy physics. The next paragraphs illustrate this mutual benefit through a few examples.

- CUSBO: Access to CUSBO allowed a group from Queen's University, Belfast, led by Jason Greenwood, investigating amino acids with near-IR few-cycle pulses and attosecond pulses. It led to the first direct measurement of ultrafast charge migration in a biomolecular building block. In this framework CUSBO has acquired a new expertise in the production of biologically relevant molecules in the gas phase, which is now available for other users in the field of application of attosecond pulses to complex molecules.

- LUND: Within a project on photochemistry and photophysics of melanin pigments and its building blocks the user group headed by Prof. Alessandro Pezella (University of Naples Federico II) made several Laserlab-Europe funded campaigns. During the latest campaign, in the spring of 2015, the collaboration was extended to include Prof. Per Uvdal of the Chemical Physics Division and the MAX-IV Laboratory, Lund University, with the aim to explore the use of various X-ray synchrotron techniques for the study of the role of metal content in melanin pigments, and compare the results with those of laser-based techniques. This campaign demonstrated positive synergies between laser-based and synchrotron-based techniques, frequently used by completely different research groups.

- CELIA: A very fruitful experiment has been carried out on the 2 µm IR source and the High Harmonic Generation in the tight focusing regime by an Imperial College team (A. Zair et al) who is expert in post compression via filamentation. The strong synergy between the host and the users resulted in several papers, demonstrating the new capabilities of the 2 µm IR light source and this few cycle new source, now offered to external scientists.

- SLIC: Prof. Zepf's group (Belfast University) has developed a new scheme to produce a weak prepulse superposed to an ultra-intense laser beam, at a perfectly controlled delay before the main laser pulse. Implemented on the high-contrast UHI100 laser beam, this scheme provides a very simple way for precise control of the density gradient of dense plasmas produced at the surface of solid targets. The SLIC group and its visitors are now extensively using this scheme, which has ensured the success of several original experiments.

- ICFO: Access visits to ICFO have led to new collaborations and improved access opportunities for external scientists, in the form of a new simulator and working brain imager prototype, both available for access.

- LASERIX: D. Ursescu (INFLPR in Romania) proposed exploring an innovative soft x-ray laser pumping scheme which appeared to be well suited for improving a pumping method developed at that time on LASERIX. A successful demonstration of a mix of these two techniques was achieved on a large variety of lasing elements, demonstrating for the first time in Europe harmonic seeding of a soft x-ray laser in a solid target plasma. The mixed scheme plus harmonic seeding is both efficient and easy to handle, and will be available to users in the future.

- PALS: A pure hydrogen plasma was produced by interaction of the PALS laser beam with a thin strip of frozen hydrogen produced by a unique helium cryostat developed at INAC/SBT in France. This was the first ever proof of principle of using hydrogen ice as a laser target for efficient acceleration of protons. An international team from the ELI-Beamlines project operated the proton diagnostics. A fs interferometer-polarimeter developed at IPPLM Warsaw made it possible to image the hydrogen plasma with a high temporal and spatial resolution. Both the above instruments highly improve (PALS) access opportunities for external scientists.

- CLF: Access to CLF-ULTRA by Dr Susan Quinn and Professor John Kelly (University College Dublin) has led to the formation of a collaboration between UCD, the University of Reading (Professor Christine Cardin), and Diamond Light Source (Professor Thomas Sorensen). The project aimed at combining near-atomic resolution structural data and ultrafast dynamic studies to probe the exact locations of the initial processes in DNA of both sensitized and direct UV-induced photo-damage. The consortium played a key role in the successful bid to fund the "LIFEtime" system at CLF-ULTRA, a new facility for time resolved studies of biological process (fs to ms time scales). LIFEtime will be available for external users from 2017.

- HIJ-FSU: As a result of an access campaign at the JETI facility at HI-Jena, the existing probing capabilities at JETI could be extended significantly. It is now possible to include Jena's unique experimental probing infrastructure - a few-cycle probe pulse unit synchronized to the 40-TW JETI-system - into state-of-the-art particle-in-cell simulation codes. This combination allows for the first time a detailed interpretation of the experimental results yielding high-resolution insights into laser-plasma interactions. These improved probing tools can be used by other external users at JETI.

c) Networking activities as supporting measures for research, facility operations, RI development and ensuring long-term sustainability of the Consortium as a virtual infrastructure of European dimension:

Networking activities have been the glue holding the Consortium together, effectively making it more than the sum of its national components. The expected long-term impact was the sustainability of a *world-class virtual laser Research Infrastructure of European dimension*, lasting beyond the time scale of EU Framework Programmes and complementing national research efforts on the one hand, and future pan-European laser RIs on the other.

Networking activities may be classified, with considerable cross-links between them, as
1. General management, administration and strategic development of a European virtual laser RI
2. Supporting measures for its business segment “improvement of internal research capacities” (JRAs)
3. Supporting measures for its business segment “User services” (Transnational Access and related services)

The first set of activities included short-term measures and tools for day-to-day operation, comprising “The Virtual Laser Infrastructure” and “Publicity and Dissemination”, with tasks including on-line project management, document and content management, virtual meetings, web presence and printed matters. It also comprised “International Relations”, regarding the fact that Laserlab-Europe has widely been considered as a model to follow in other global regions in the world. In addition, this activity set also focused on long-term sustainability in the operation of a European virtual RI, and the development of new sub-units (national RIs), especially in new Member States, through the “Network of National Contact Points” and “Foresight activities”. Within the European Research Area, Laserlab-Europe had given itself a tool, the network of National Contact Points, to establish a formal dialog with the national projects. By issuing formal advices and support to selected projects, Laserlab-Europe tried to contribute to coordinate national initiatives of new laser infrastructures, in particular the ESFRI project ELI which, in itself, is a distributed Infrastructure.

The second set of activities included scientific and technological exchanges, and mainly focused on the improvement of internal research activities besides the JRAs themselves. This included operation of the new extended pool of infrastructures in a unified and concerted way through adequate pooling of equipment, common experimental campaigns, unification of procedures, benchmarking, and the implementation of JRA results into Transnational Access opportunities.

The third set of networking activities included user community training, Transnational Access management, and monitoring Infrastructures-Users connections. It jointly induced a strengthening and an expansion of the laser user community, both geographically and thematically. Geographically, targeted actions towards regions with emerging user communities, mainly the northern, eastern and south-western extremities of Europe, have increased the general awareness and experience of scientists on access opportunities. The action of National Contact Points has been crucial in this respect; regional user community training courses were also important. Thematically, targeted user training courses and user meetings increased the bonds with other scientific domains, like particle physics, accelerator physics, synchrotrons and FELs, chemistry, biology and medical sciences. Again, the success did not depend on networking alone, but on the joint action of networking and JRAs.

Networking impacts consisted in
- Further development of a corporate identity for the Consortium as a whole, including unified internal and external representation,

- Development and implementation of best practices in the operation of the de-centralised sub-units (national RIs) of the European virtual RI,
- Better exploitation of the entity of European academic resources through the development of new national RIs as integral elements of the national research policies, especially in new Member States,
- Development of a common European research strategy and strategic roadmaps for the future of laser science through Foresight Activities, thus strengthening and ensuring the strong global position of European laser research,
- Increased links with non-European laser networks, thus strengthening the international context of European laser RIs,
- Strengthening and supplementing the impacts of the Transnational Access and JRAs through accompanying networking activities.

1.4.2 Main dissemination activities and exploitation of results

Dissemination of research results is a matter of importance and scientific ethics in publicly funded research. Hence, dissemination and publication activities were subject to a work package of their own, WP3 “Publicity and Dissemination”, with the overall objective of increasing the general awareness of the achievements and opportunities offered by Laserlab-Europe, to a very broad audience, from the general public, to fellow scientists, potential users of laser-based tools in very diverse scientific fields, and to the regional, national and European public organisations. In particular, the work package comprised maintenance of a web portal (www.laserlab-europe.eu), edition of a periodic Laserlab-Europe Newsletter and other promotional material, advertisement of Transnational Access opportunities through various channels, including the internet and printed matters, and representation of the consortium in major scientific events, international conferences, trade fairs and exhibitions. Most dissemination activities were also web-based.

All partners took an active role in spreading the information about the project in their own spheres and countries. Moreover, the infrastructures involved in Transnational Access and Joint Research Activities were responsible for the publication of their results. Scientific results have been documented on the Laserlab-Europe webpage through research highlights sections and through the databases for publications resulting from the JRA or from transnational access projects. At the time of submitting this report, the databases comprised about 470 publications from JRA and about 170 publications from transnational access projects, among them several in highly ranked journals such as Nature, Nature Physics, Nature Materials, Physical Review Letters, Science, etc. This number will increase considerably after the end of the project, when all scientific activities are completed and the results obtained can be published. All publications may be found at http://www.laserlab-europe.eu/publications

Several of the Networking activities involved the organisation of scientific workshops and conferences, which were another means of disseminating scientific results, and synchronising Laserlab-Europe’s research activities with the European and global scientific environment.

In addition, the work package WP6 “Access Management and Monitoring Infrastructures-Users Connections” contained as one important element the organisation of annual laser user meetings. They successfully brought together a significant number of users and facilitate and foster their exchanges with the infrastructures and among the scientific user community. In particular, this was the main forum for the users to present their scientific results, frequently complemented by selected contributions from international experts in the respective fields.

One of the main objectives of the JRA activities was the improvement of the combined research capacity of the virtual infrastructure, and the creation of new access opportunities (state-of-the-art instrumentation) for European users. Exploitation of the results along these lines has been common practice in the operation of Laserlab-Europe, and has been one of the foundations of its scientific reputation and success. The exploitation included the internal dissemination of research results, in some cases also equipment and equipment-related know-how, among the partner infrastructures in order to raise the overall level of their facilities. Part of this was done through the work package WP4 “Scientific and technological exchanges”.

Certain research activities have produced technology that is, in addition, commercially exploited through patents and/or licensing agreements or through spin-off companies. Examples are given in section 1.4.1 above. As a result of the research conducted in the Laserlab JRA ten applications for patents were submitted.

At the beginning of the project, the partners of the project agreed on a Consortium Agreement stating exact rules for patent and license applications and for the commercialisation of the results of the project, including agreements on the management of knowledge and of intellectual property rights. The adherence to these regulations was monitored by the JRA Board and the Management Board.

1.5 Project public website and contact details

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