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Project Report

Light Sources in Europe—Case Study: The COMPACTLIGHT Collaboration †

Nikolaos Gazis [1], Eugene Tanke [1], Theodoros Apostolopoulos [2], Katerina Pramatari [3], Regina Rochow [4] and Evangelos Gazis [5,6,*]

1. European Spallation Source, 225 92 Lund, Sweden
2. Department of Informatics, Athens University of Economic and Business, 104 34 Athens, Greece
3. Department of Management Science & Technology, Athens University of Economic and Business, 104 34 Athens, Greece
4. Elettra-Sincrotrone Trieste S.C.p.A., 34149 Trieste, Italy
5. School of Applied Mathematical and Physical Sciences, National Technical University of Athens, 157 80 Athens, Greece
6. Institute of Accelerating Systems & Applications, 100 24 Athens, Greece

* Correspondence: Evangelos.Gazis@cern.ch

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Abstract: The light sources currently existing or under development in Europe address needs in the Central and Northwestern regions, whereas in the Southeastern European region there is no facility of this kind. The CompactLight collaboration, an H2020 funded project, is going to deliver a Conceptual Design Report (CDR) of a novel generation X-ray Free Electron Laser (XFEL) facility which is compact, innovative, relatively cheap and to be implemented for industrial and medical applications. The CDR will facilitate technological updates of the many European region institutions and enable them to construct a novel light source. Cost and risk analysis, as well as technology transfer and market survey of the project results are also discussed.

Keywords: light source; XFEL; high gradient accelerator facility; industrial and medical applications; cost and risk analysis; technology transfer and market survey

1. Introduction

There are many large-scale accelerator infrastructures in Europe, building the future in key areas of research and development for the upcoming decades [1]. Synchrotron Radiation (SR) has become a fundamental and indispensable tool for studying matter, as shown by the large number of facilities in operation worldwide, which is close to eighty and serves tens of thousands of users every year. The impact of SR across these disciplines cannot be doubted as evidenced by the five Nobel prizes that were awarded in the past twenty years to scientists whose research had been made possible by SR [2].

A synchrotron based light source is made up of several key components: a source of electrons, a linear accelerator, a booster synchrotron and a storage ring. Electrons are generated in an electron gun, and accelerated in bunches in the linear accelerator before continuing their journey into the booster synchrotron where they are further energized. Once the right energy is reached, the electrons are injected into the storage ring where several hundred bunches of electrons circulate at just under the speed of light. At various points around the storage ring, these electrons pass through specially designed magnets and emit brilliant synchrotron light. This light is channeled down to the experimental stations, which are called beam-lines. Many experiments can run simultaneously making a synchrotron a high-throughput environment with the ability to support a large community of scientists. There are more than 50 light sources producing synchrotron light with 60,000 users worldwide, as given by LEAPS (League of European Accelerator-based Photon Sources, https://www.leaps-initiative.eu/) [3].

X-ray Free-electron lasers (XFELs) are also accelerator-based light sources, utilizing electrons to generate beams of light with unique properties. Unlike circular synchrotrons, XFELs are based on a linear accelerating structure. The electron beam is passed through magnetic undulators up to 300 m long. These arrays of magnets can be manipulated to enable the production of the required light for a given experiment. Through complex interactions between the photons and electrons in the undulator, the electrons arrange themselves into thin disks, which emit light in a highly synchronized way. The resulting light from these minute electron disks is pulsed and laser-like. This enables the study of processes at the atomic scale across a range of timescales, reaching the femtosecond, which was previously inaccessible to researchers. Each XFEL possesses a number of beam-lines enabling research into physical and life sciences.

Synchrotron Radiation has become a fundamental and indispensable tool for studying matter, as shown by the large number of these facilities in operation worldwide.

Light sources encompass both the synchrotron light source community, which produce highly intense continuous beams, and the free-electron lasers community, producing high intensity short pulsed laser-like beams.

Light source facilities have been working alongside each other in Europe successfully for years, supporting world-class science. In the recent past alone, light source facilities have welcomed 24,000 direct users, who have had an impact on a wider network of 35,000 researchers, with 23,400 unique articles published in peer-reviewed journals. (Data from the 1st page of https://lightsources.org)

The LEAPS collaboration offers a step change in European cooperation, uniting 16 organizations representing 19 facilities through a common vision of enabling scientific excellence solving global challenges, and boosting European competitiveness and integration. This will be achieved through a common sustainable strategy developed in consultation with all stakeholders, including national policy makers, user communities and the European Commission.

2. Societal Impact of Light Source Applications

New technology, new treatments and the implementation of innovative discoveries for the social prosperity and security of European citizens today and in the future depend on meeting increasingly demanding challenges. These can be found in a variety of fields (e.g., basic science, energy, transport, healthcare, food, safety, sustainable living, culture heritage and archaeology) and must all be tackled within a thriving, inclusive economy. The use of X-ray FELs, in the short time that they have been available, has already led to significant insights in a number of scientific fields such as atomic, plasma, solid-state physics, and macromolecular crystallography [4–6]. There are many references [7,8] suggesting the shortest and brightest pulse for future XFEL facilities. More specifically. the shortest pulse duration, down to 1 fs, is exclusively needed for the innovative applications in femtosecond molecular crystallography in biology [9] and in femtosecond chemistry [10]. The capability of single-shot detection of diffraction signals using a femtosecond X-ray pulse enables researchers to obtain intrinsic structures that are free from structural damage caused by the radicals and reactants produced by X-ray irradiation. This makes it possible to analyze the structures of micro- or nano-sized protein crystals in physiological conditions [11]. Gaining a better understanding of the world around us demands new technology, all of which points to an increased role and reliance on highly sophisticated analytical tools like accelerator-based light sources to provide the most incisive means of measuring and unraveling atomic and molecular structures of the world around us. Researchers are developing new exploitation techniques, increasingly based upon enhanced output from FELs such as two-color pulses, femtosecond and sub-femtosecond photon pulse lengths [12–14]. The information revealed at this scale can have a transformational effect on science and technology.

2.1. Health

Recent successes by researchers include a new synthetic vaccine for polio, a range of therapeutic drugs for breast cancer, new materials for prosthetics and boundaries of 3D imaging being pushed down to the cellular level. Synchrotron light source facilities may enable whole cell imaging to understand the development of disease at this level, while free-electron lasers (FELs) will allow for the investigation of the dynamics of biological processes on the atomic scale. The academic contribution made in structural biology is enormous, with over 14,500 protein structures deposited in the open access Worldwide Protein Databank in the last 5 years by light sources. The pharmaceutical industry research has concentrated on exploiting protein crystallography to assist drug discovery programs.

2.2. Energy

The light sources have been at the forefront of efforts to develop advanced energy materials such as those involved in the new generations of solar cells, new energy efficient information technologies and solutions for energy storage (e.g., the design of lithium-ion batteries has already been improved and alternatives such as sodium-ion batteries investigated). In addition, significant research continues to be directed towards novel fuel cells, which offer the potential for 'zero emission' energy sources. In the future, brighter light sources and FELs in particular, will enable more measurements to study the dynamics and function of cleaner energy devices, and to optimize their development under realistic conditions.

The access to locally available light sources enables Europe to speed up innovation and consolidate its position as a global leader in science with a detailed understanding of how catalysts work at the atomic level; by enabling cleaner air, improving health and ensuring more efficient use of natural resources.

3. Study Case: CompactLight Collaboration

3.1. General

Synchrotron Radiation facilities have seen, during the past decades, an impetuous growth as they are a fundamental tool for the study of materials in a wide spectrum of sciences, technologies, and applications. The last generation of Synchrotron Light Sources was based on single-pass Free Electron Lasers (FELs), driven by linacs, and featured an unprecedented performance in terms of pulse duration, brightness and coherence.

The demand for new FEL facilities is continuously increasing worldwide, spurring plans for new-dedicated machines. The lightsources collaboration [15] reports that there is no light source from Czech Republic to the rest of Eastern and Southern Europe, the Middle East (except the SESAME project) [16] and the Scandinavian (except Sweden), Baltic, Iberian and North African countries, as shown in the map in Figure 1.

A number of other European countries have considered or are actively considering FEL facilities at the present time, including the UK, Turkey, Sweden, the Netherlands and France. The strong scientific case for FEL beams is apparent from the inability of present facilities to meet the demands of the scientific community. At the LCLS [17] facility, the number of proposals has increased from ~30 in 2009 to close to 200 in 2014, of which only 20% are currently scheduled. Similarly, at the FERMI [18–20] facility, at the research center Elettra–Sincrotrone Trieste, Italy, a little more than 30% of the proposed experiments are currently scheduled with a similar situation existing at FLASH [21].

This has led to a general reconsideration of costs and spatial issues, particularly for the Hard X-ray Sources, driven by long and expensive multi-GeV normal conducting linacs.

For these machines the use of an optimum combination of emerging and innovative accelerator technologies can greatly reduce costs and capital investment, opening the way to the construction of a multitude of affordable "Regional Facilities".

Figure 1. A map of existing or under construction Light Sources in Europe and surrounding areas (https://lightsources.org/lightsources-of-the-world/europe/).

The CompactLight [22,23] project intends to design a hard X-ray FEL facility beyond today's state of the art, using the latest concepts for bright electron photo injectors, very high-gradient X-band structures at 12 GHz, and innovative compact short-period undulators, summarized briefly as follows:

- High brightness electron photo-injectors
- Very high gradient accelerating structures, 100 MV/m
- Novel short period undulators

In addition, CompactLight has options for soft X-rays and for a Compton source.

To put this into perspective, the existing FELs facilities in the European Union (FERMI, FLASH and FLASH II [24]) are operating in the soft X-ray range, while other two facilities (SwissFEL [25] and EuroXFEL [26]), which will operate in the hard X-ray scale. The proposed facility will benefit from a lower electron beam energy due to the enhanced undulator performance, be significantly more compact, as a consequence both of the lower energy and of the high-gradient X-band structures, have a much lower electrical power demand and a smaller footprint. The CompactLight facility gathers the world-leading experts in these domains, united to achieve two objectives: disseminate X-band technology as a new standard for accelerator-based facilities and advance undulators to the next generation of compact photon sources, with the aim of facilitating the widespread development of X-ray FEL facilities across and beyond Europe by making them more affordable to build and to operate.

The CompactLight Collaboration consists of 24 partners, mainly from Europe, including from Turkey, China and Australia including four associate partners from Europe.

3.2. CompactLight Innovation

The main figure of merit for SR is the brightness, which defines the intensity of radiation, within a given bandwidth around the desired wavelength, focused onto a sample of given area, with a particular solid angle.

A major factor in the cost of the construction of FELs is the accelerator technology adopted. The majority of existing facilities utilize S-band linear accelerators given the maturity of the technology. However, this technology, although consolidated through many decades of use is not optimal. At comparable accelerating fields, a higher frequency accelerating structure can achieve higher gradients and lower power requirements than those produced by lower frequency structures.

The successful construction and operation of SACLA [11] (Japan) at a C-band frequency is testimony of the effectiveness of a higher accelerating frequency. In this case, an 8 GeV electron beam with the characteristics required to drive an FEL can be generated in the space of 400 m compared to 600 m at the S-Band (inclusive of injector and bunch compressors). Subsequently, SwissFEL also adopted C-band technology. The use of X-band technology further improves the situation and one can expect to more than halve the required length of the accelerator and associated infrastructure compared to these machines. For large-scale accelerator projects such as synchrotron radiation light sources and FELs the cost breakdown is typically: 70% in civil engineering, accelerator and the first beamlines, and 30% for personnel and management. Parametric scaling of the accelerator length can result in 20 to 25% savings.

The CompactLight design study, based on validated high-gradient X-band and novel undulator technologies, will also enable upgrades of existing FELs (e.g., FERMI) to higher energies within physical space limitations, which would otherwise not be possible due to the limited accelerating gradients of the S- and C-band structures. It will also allow existing facilities to expand their user communities and scientific programs taking advantage of the shorter produced photon wavelengths. In fact, high-frequency X-band structures can also run at low gradients and at a high repetition rate (kHz regime), enabling a new set of operational scenarios for high average power X-ray FELs, currently in high demand for scientific and technological application.

The expansion of the use of X-band technology, which this design study has the potential to stimulate, will also benefit the particle physics community such as future energy frontier lepton colliders (e.g., CLIC [27]), or other Higgs factories, through the industrialization of the technology and the broadening and enhancing of the skill base in this area.

Concerning the industrial applications, many study groups have suggested high-power FELs, operating at 13.5 nm, as a possible high-volume lithography source for manufacturing computer chips and electronic components. For this type of application, care needs to be taken to guarantee very high levels of reliability and availability of the FEL facility.

3.3. Objectives

The key objective of the CompactLight Design Study is to demonstrate, through a conceptual design, the feasibility of an innovative, compact and cost effective XFEL facility suited for user demands identified in the field of science.

The main cost driver for every XFEL is the beam energy. By implementing room temperature in the vacuum device, it is possible to achieve a 0.1 nm wavelength output at 5.8 GeV. A new generation of superconducting undulators for FELs with very low average beam currents, and consequently much smaller wakefield-induced heat loads (taking the much smaller bunch lengths into account) on the cryogenic vacuum beam screen, are able to operate with a similar magnet beam aperture as permanent magnet undulators. In this case preliminary calculations suggest that an XFEL could generate 0.1 nm wavelength output already at 4.6 GeV, which is an ~20% reduction in the beam energy. A simplified layout of the proposed FEL is shown in Figure 2.

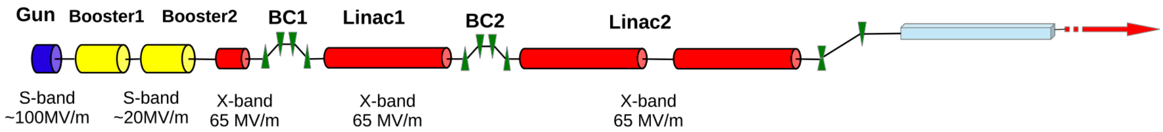

Figure 2. Layout of an XFEL (X-ray Free-Electron Laser) facility.

A strong collaboration of CompactLight with CERN and in particular with the CLIC Collaboration to make a compact and more affordable XFEL in the next decade, the CLIC X-band accelerator technology is looking like it will be a very promising solution to fulfill this aim. The performance requirements for the main linac of CLIC, a TeV-range electron-positron collider, are quite demanding [27]. The most important parameters are an accelerating gradient of 100 MV/m, low breakdown rate, micron-tolerance alignment and a high RF-to-beam efficiency (around 30%). Figure 3 shows a photograph of a successful high accelerating gradient X-band structure prototype at gradients above 100 MV/m, an important milestone.

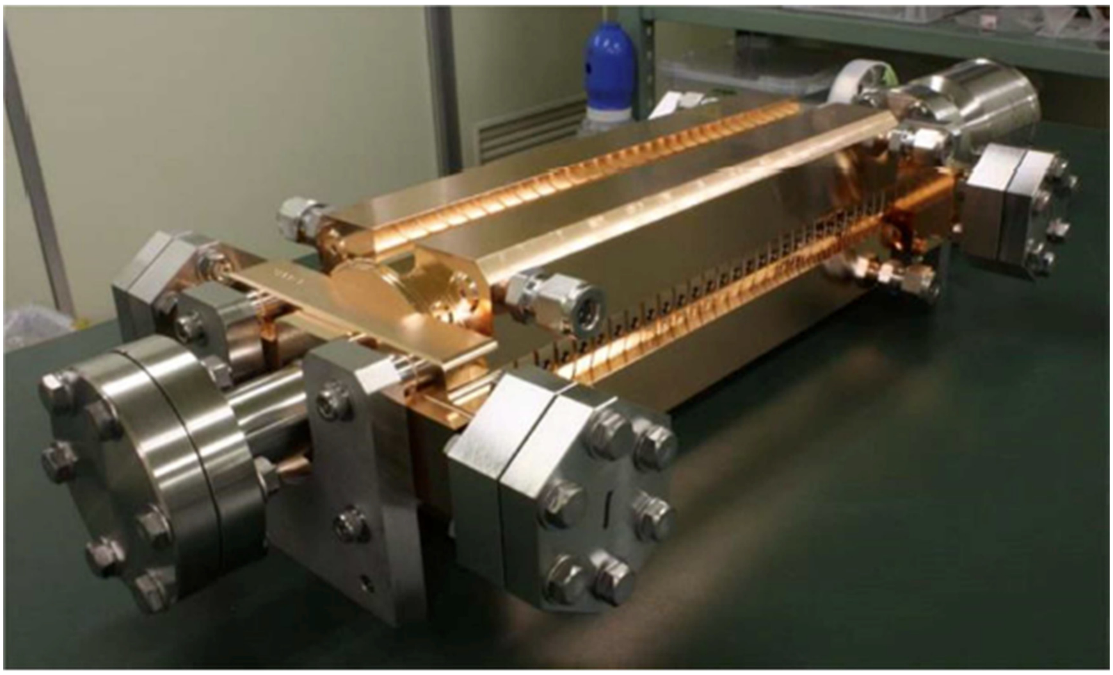

Figure 3. The CLIC T24 X-band accelerating structure, operated up to 120 MV/m, (CLIC CDR Vol1, CERN, 2012).

The compact and modular CLIC X-band technology can also be exploited to generate 3 GeV electrons over a short distance and then extended to generate a 6 GeV or greater beam to drive a FEL. The high-level technical specifications on which the CompactLight will be based are listed in Table 1.

The major novel and innovative advantages can be summarized as follows:

- Lower emittance and higher repetition-rate photo-injectors
- High-gradient linacs: Gradients in excess of 100 MV/m are now routinely achieved.
- High-efficiency klystrons: Techniques to bring efficiencies above 60% at high frequency have been demonstrated.
- Advanced concept undulators: Cryogenic permanent magnet undulators and superconducting undulators have both been demonstrated and successfully operated on 3rd generation light sources in recent years.

- Improved diagnostics including X-band deflectors for longitudinal bunch dynamics.
- Better beam dynamics and optimization tools including those developed for linear colliders.

Table 1. CompactLight accelerator parameters.

Parameter	Value	Unit
Minimum Wavelength	0.1	nm
Photons per pulse	$> 10^{12}$	
Pulse bandwidth	<< 0.1	%
Repetition rate	100 to 1000	Hz
Pulse duration	< 1 to 50	fs
Undulator Period	10	mm
K value	1.13	
Electron Energy	4.6	GeV
Bunch Charge	< 250	pC
Normalized Emittance	< 0.5	µrad

4. Cost and Risk Analysis

4.1. Cost Analysis

Cost and performance models of the technical systems will be based on simulations and prototypes. These and existing models of other light sources and middle to large size accelerator facilities [28–31] will be taken into account and worked upon by experts from the Athens University of Economics and Business (AUEB) and the Institute of Accelerating Systems and Applications (IASA). The scope of this work includes the four technical systems, which cover the injector, linac, undulator and beam dynamics respectively. This activity will also take into account the costs and estimated budgets required for the construction and operation of these facilities. Comparison of costs will be made with conventional technologies and will take into account already committed investments. Comparison of costs will also be made with XFEL facilities worldwide, both planned and under construction. Preliminary estimates, taking into account the nominal electron energy and hard X-rays production, show lower costs than for the existing other XFEL facilities.

4.2. Risk-SWOT Analysis

Here, risks are defined as the probability of occurrence times the impact of an event and should be managed properly, such as to avoid results with a negative impact on project economics, e.g., cost overruns and time delays. As an example, a properly implemented integrated risk management process leads to a successful infrastructure project during the design phase.

There are many risk management standards, i.e., PMBOK, CAN/CSA-Q850-97, RISMAN, FERMA and IRM, IEC 62198:2013, PRAM, BS6079-3: 2000 and ATOM. These standards are studied intensively based on criteria such as risk identification, risk assessment, analysis and treatment, risk response, risk control, monitor and review, etc. Based on a study of risk management for CompactLight, the need to improve the factors that influence the quality of performance of CompactLight became evident.

The risk analysis of our project was examined, primarily, via the Strength–Weakness–Opportunities–Threats (SWOT) analysis which helps the identification of the advantages and disadvantages of the project, in order to avoid fatal solutions or selections for its integration and construction procedure.

➢ The strengths analysis yielded the following advantages:

  - New design with improved specifications than existing facilities
  - Active and broad collaboration with experience teams in the project
  - Industrial partnership

- Scientific, Engineering, Finance & Economical academic partnership
- Less expensive final product

➢ The Weaknesses analysis yielded the following considerations:

- Final technological option(s) to various parts yet to be decided
- Effort to cover more sub-areas of X-ray production

➢ The Opportunities analysis yielded the following possibilities:

- Large areas without a light source in Europe and elsewhere for implementation of our final product
- Cooperation development with institutions and countries to commercialize our product
- Future member of the XFEL network

➢ The Threats analysis yielded the following considerations:

- Parallel XFEL projects under current development
- Different technology projects providing S-/C-band X-rays or some of them

As part of this analysis, identification nodes and failure modes of the project were defined:

- Identification Nodes: RF-gun, Injector, Linac, Bunch Compressor, Undulators, Klystrons, Power system, Beam control system, Time schedule, Over costing.
- Failure Modes: Construction delay, Commissioning, Operation, Technical failure, Power off, Time delay, Budget limit.

The Risk Analysis is conducted in two steps. Firstly, for each potential failure a YES/NO decision is made to retain credible failures only. Secondly, worst case scenarios for the nodes located in the RF, magnets, undulators, control of the machine and power are identified and a descriptive probability for each of the mishaps is assigned. Then a descriptive analysis of the causes and consequences of each credible failure is made and a gravity number of 1 to 3 is assigned to each event. Failures of gravity 1 do not create any risk, neither to machine nor to other sources. For the failures of gravity 2 and 3, the associated risks are described and recommendations are formulated [32].

Some preliminary results of the risk analysis for the Compact Light project are listed in Table 2, including the risk analysis during the various phases of the project. In this table, it is concluded that there is no gravity failure of size 3 as a well-structured CDR will be delivered. In addition, the gravity failure with gravity 2 is related to the possible delay of the construction phase; it depends on the stakeholder that will build this facility and on the off power conditions, during the XFEL operation. These latter ones in turn depend on the available power structure of the facility.

Table 2. A draft Risk Analysis estimation.

Phase	RF-Gun	Injector	Linac	Bunch Compressor	Undulators	Klystrons	Power System	Beam Control System	Time Schedule	Over Cost
Construction	2	2	2	2	2	2	2	2	2	1
Commissioning	1	1	1	1	1	1	1	1	1	1
Operation	1	1	1	1	1	1	1	1	1	1
Technical failure	1	1	1	1	2	2	2	1	1	1
Power off	2	2	2	2	2	2	2	2	2	2
Time delay	1	1	1	1	1	1	1	1	1	1
Budget limit	1	1	1	1	1	1	1	1	1	1

5. Transfer Technology and Market Survey

One major effort in the CompactLight project is related to the long-term goal of providing a degree of standardization such that FELs become facilities that can be provided by industry. The "Strategy

Report on Research Infrastructures", Roadmap 2016, asserts: "SR facilities are very powerful attractors and contribute to European scientific and industrial competitiveness" [33]. CompactLight has as the primary project objective a compact hard X-ray FEL facility design, with options for soft X-rays and for a Compton source, and targets the major technology areas important for an XFEL: the gun and the injectors, beam acceleration and RF production, and undulators and photon production. Additionally, technologies for compact, high-precision, diagnostics will also be reviewed and studied. Each of these R&D areas has large potential for application that go well beyond CompactLight itself.

The innovative results of the CompactLight project can be summarized as follows:

Advanced Applications: Nano materials, Metallurgy, Electronics, Chemistry, Biology, Protein structure, DNA radiation damage, Molecular Crystallography, Super Microscopy, Agriculture, etc.

The hard X-ray photons of our XLS collaboration with 0.1 nm wavelength has the privilege of mapping the atomic structure of materials (including bio-molecules and nanometer scale structures) and to track ultrafast phenomena of interest with currently available techniques.

Providing Advanced XFEL Components: Photocathode/Laser, RF Gun/Injector, LINAC, Undulator, Beam Instrumentation.

The cutting-edge technology components can be fruitfully constructed and distributed to other labs or industrial units. The total design of the X-FEL can also be provided as a compact, short length and less expensive powerful special X-ray source for particular applications and science.

In addition to the aforementioned items related to knowledge and technology transfer, it is also important to get feedback from the users forum and define new requirements for future users of our project.

The industrialization and cost reduction of the high-power RF system, klystrons, modulators, pulse compressor and waveguide network, as well as the tight-tolerance, high-gradient accelerating structures, will be led by CERN and carried out with the support of a private company (VDL ETG). It is noted that the VDL ETG Precision Technology is specialized in the co-development of high precision parts, sub-assemblies, prototypes and modules. Another private company, KYMA S.A., established in August 2007 by Elettra Sincrotrone Trieste, has as its primary purpose to design, realize and install the undulators for the FERMI@Elettra FEL project, including participation in the final specification of the undulators. Since its establishment, KYMA became a reference supplier in the light source community, with almost fifty insertion devices designed and manufactured. KYMA is now recognized as a qualified partner for the design and development of this kind of equipment.

The intellectual property (IP) of our project lies at the heart of innovation and competitiveness around the world as well as in the European Union. The intellectual property rights (IPRs) are protected mainly through patents, trademarks and copyright. They enable individuals and companies to earn recognition and/or financial benefit from what they invent or create. Taking into account the right balance between innovators and public interest, IP aims to foster an environment in which creativity and innovation can flourish. The EU has shaped a framework (EU IPRs Policy for H2020 Projects, H2020-Annotated Model Grant Agreement Dec 2018.) that defines and protects innovations and creations through IP. This framework mainly comprises of directives and regulations protecting copyright, trademarks, patents, designs and geographical indications.

6. Conclusions

This work presents Synchrotron Radiation and XFEL facilities, both existing and under construction in and around Europe. It establishes the need for more XFEL units to provide tools for science, energy, health and many other applications; promoter which will proceed with the upgrade of the industrial product level. The CompactLight project is aimed at the development of an innovative next generation XFEL of hard X-rays emission that is compact and less expensive; taking advantage of CLIC accelerator technology (accelerating structure of 100 MV/m). The risk and cost analysis of the project with the definition of a final risk table, as well as the transfer technology and market survey work with certain impacts on scientific and applied domains, were also presented. The cooperation of academics with industrial CompactLight partners provides the methodology to disseminate our technological results to the European industry.

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References

1. Romaniuk, R.S. ARIES—Development of Accelerator Technology in Europe 2017–2020: Global and Local Consequences. *Int. J. Elec. Telecommun.* **2017**, *63*, 109–117. [CrossRef]
2. The Five Nobel Prizes That Have Been Made Possible by SR Were Awarded in 1997, 2003, 2006, 2009, and 2012. Available online: https://www.nobelprize.org/prizes/lists/all-nobel-prizes/. (accessed on 15 August 2019).
3. League of European Accelerator-based Photon Sources LEAPS, Light Sources for Europe—Strengthening Europe's Leading Role in Science and Innovation. Available online: https://www.leaps-initiative.eu/news/leaps_brochure/ (accessed on 12 August 2019).
4. Bostedt, C.; Boutet, S.; Fritz, D.M.; Huang, Z.R.; Lee, H.J.; Lemke, H.T.; Robert, A.; Schlotter, W.F.; Turner, J.J.; Williams, G.J. Linac coherent light source: The first five years. *Rev. Mod. Phys.* **2016**, *88*, 015007. [CrossRef]
5. Miao, J.W.; Ishikawa, T.; Robinson, I.K.; Murnane, M.M. Beyond crystallography: Diffractive imaging using coherent x-ray light sources. *Science* **2015**, *348*, 530–535. [CrossRef] [PubMed]
6. Piancastelli, M.N.; Simon, M.; Ueda, K. Present trends and future perspectives for atomic and molecular physics at the new X-ray light sources. *J. Electron Spectrosc. Relat. Phenom.* **2010**, *181*, 98–110. [CrossRef]
7. Department of Energy. FY 2018 Congressional Budget Request—Science, DOE/CF-0131. May 2017; Volume 4. Available online: https://science.osti.gov/-/media/bes/besac/pdf/Reports/Future_Light_Sources_report_BESAC_approved_72513.pdf (accessed on 13 August 2019).
8. European Strategy Forum on Research Infrastructures (ESFRI). *Strategy Report on Research Infrastructures*; Roadmap 2018, Science and Technology Facilities Council: Swindon, UK, 2018. Available online: http://roadmap2018.esfri.eu/media/1060/esfri-roadmap-2018.pdf (accessed on 16 August 2019).
9. Martin-Garcia, J.M.; Conrad, C.E.; Coe, J.; Roy-Chowdhury, S.; Fromme, P. Serial femtosecond crystallography: A revolution in structural biology. *Arch. Biochem. Biophys.* **2016**, *602*, 32–47. [CrossRef] [PubMed]
10. Zewail, A.H. Femtochemistry: Atomic-Scale Dynamics of the Chemical Bond. *J. Phys. Chem. A* **2000**, *104*, 5660–5694. [CrossRef]
11. Yabashi, M.; Tanaka, H.; Ishikawa, T. Overview of the SACLA facility. *J. Synchrotron Radiat.* **2015**, *22*, 477–484. [CrossRef] [PubMed]
12. Schoenlein, R. *New Science Opportunities Enabled by LCLS-II X-ray Lasers*; Report No. SLAC-R-1053; SLAC National Accelerator Laboratory: Menlo Park, CA, USA, 2015.
13. Andersen, J.; Fernandes Tavares, P.; Isaksson, L.; Kotur, M.; Lindau, F.; Mansten, E.; Olsson, D.; Tarawneh, H.; Thorin, S.; Curbis, F.; et al. The Soft X-ray Laser Project @ MAX IV: A Science Case for SXL. In Proceedings of the IPAC2017, Copenhagen, Denmark, 14–19 May 2017.
14. *Free-Electron Laser (FEL) Strategic Review*; Science and Technology Facilities Council: Swindon, UK, 2016; Available online: https://stfc.ukri.org/files/fel-report-2016/ (accessed on 16 August 2019).
15. Lightsorces.org. Available online: https://lightsources.org/lightsources-of-the-world/europe/ (accessed on 12 August 2019).
16. SESAME. Available online: http://www.sesame.org.jo/sesame_2018/ (accessed on 12 august 2019).
17. Bane, K.L.F.; Decker, F.-J.; Ding, Y.; Dowell, D.; Emma, P.; Frisch, J.; Huang, Z.; Iverson, R.; Limborg-Deprey, C.; Loos, H.; et al. Measurements and modeling of coherent synchrotron radiation and its impact on the Linac Coherent Light Source electron beam. *Phys. Rev. ST Accel. Beams* **2009**, *12*, 030704. [CrossRef]

18. Bocchetta, C.J.; Abrami, A.; Allaria, E.; Andrian, I.; Bacescu, D.; Badano, L.; Banchi, L.; Bulfone, D.; Bontoiu, C.; Bracco, R.; et al. FERMI@Elettra Conceptual Design Report. *Sincrotrone Trieste* **2007**. Available online: https://www.researchgate.net/publication/236343435_FERMIElettra_Conceptual_Design_Report (accessed on 16 August 2019).
19. Allaria, E.; Appio, R.; Badano, L.; Barletta, W.A.; Bassanese, S.; Biedron, S.G.; Borga, A.; Busetto, E.; Castronovo, D.; Cinquegrana, P.; et al. Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet. *Nature Photon.* **2012**, *6*, 699–704. [CrossRef]
20. Allaria, E.; Battistoni, A.; Bencivenga, F.; Borghes, R.; Callegari, C.; Capotondi, F.; Castronovo, D.; Cinquegrana, P.; Cocco, D.; Coreno, M.; et al. Tunability experiments at the FERMI@Elettra free-electron laser. *New J. Phys.* **2012**, *14*, 113009–113028.
21. Montanari, M.; Virgilio, M.; Manganelli, C.L.; Zaumseil, P.; Zoellner, M.H.; Hou, Y.; Schubert, M.A.; Persichetti, L.; Gaspare, L.D.; Seta, M.D.; et al. Photoluminescence study of inter-band transitions in few, pseudomorphic and strain-unbalanced Ge/GeSi multiple quantum wells. *Phys. Rev. B* **2018**, *98*, 195310. [CrossRef]
22. CompactLight. Available online: http://www.compactlight.eu/Main/HomePage (accessed on 13 August 2019).
23. CERNCourier. 2017. Available online: https://cerncourier.com/eu-project-lights-up-x-band-technology/ (accessed on 13 August 2019).
24. Ayvazyan, V.; Baboi, N.; Balandin, V.; Decking, W.; Duesterer, S.; Eckoldt, H.J.; Faatz, B.; Felber, M.; Feldhaus, J.; Golubeva, N.; et al. FLASH II: A project update. In Proceedings of the FEL2011, Shanghai, China, 22–26 August 2011; pp. 247–250.
25. Milne, C.; Schietinger, T.; Aiba, M.; Alarcon, A.; Alex, J.; Anghel, A.; Arsov, V.; Beard, C.; Beaud, P.; Bettoni, S.; et al. The Swiss X-ray Free Electron Laser. *Appl. Sci.* **2017**, *7*, 720. [CrossRef]
26. Giannessi, L.; Alesini, D.; Biagini, M.; Boscolo, M.; Bougeard, M.; Lo Bue, A.; Carré, B.; Castellano, M.; Cianchi, A.; Ciocci, F.; et al. *Implementing a HHG Laser as Seed in a HGHG-FEL*; Eurofel D: Brussels, Belgium, 2008.
27. Aicheler, M.; Burrows, P.; Draper, M.; Peach, K.; Phinney, N.; Schmickler, H.; Schulte, D.; Toge, N. *A Multi TeV Linear Collider Based on CLIC Technology*; CERN: Geneva, Switzerland, 2012.
28. Schitsev, V. A phenomenological cost model for high energy particle accelerators. *J. Instrum.* **2014**, *9*, T07002.
29. COST/BENEFIT Comparison for 45 MeV and 70 MeV Cyclotrons, US DOE. May 2005. Available online: https://www.isotopes.gov/outreach/reports/Cyclotron.pdf (accessed on 14 August 2019).
30. Mentzer Morrison, R. *An Economic Analysis of Electron Accelerators and Cobalt-60 for Irradiating Food*; US Department of Agriculture: Columbus, OH, USA, 1989.
31. McGinnis, D. New Design Approaches for High Intensity Superconducting Linacs—The New ESS Linac Design. In Proceedings of the IPAC2014, Dresden, Germany, 15–20 June 2014.
32. Chorowski, M.; Lebrun, P.; Riddone, G. Preliminary Risk Analysis of the LHC Cryogenic System. LHC Project Note 177. 1999, pp. 1–69. Available online: https://cds.cern.ch/record/691872/files/project-note-177.pdf (accessed on 16 August 2019).
33. Womersley, J. Strategy Report on Research Infrastructures—ESFRI Roadmap 2016. Available online: http://www.esfri.eu/sites/default/files/20160308_ROADMAP_single_page_LIGHT.pdf (accessed on 13 August 2019).