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CompactLight global integration and cost analysis

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On behalf of the CompactLight Partnership

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Abstract

The aim of WP7 is to promote the use of the CompactLight technologies through activities that address and inform potential users and by generating instruments and documents that support them in developing and implementing their projects for the construction or upgrading of CompactLight-based facilities. D7.1 is the first version of the corresponding documentation, containing the state of the work and the results achieved by the end of 2019. It presents in particular the insights obtained so far from the dialogue with the scientific user community, preliminary results for the landscape analysis, an explanation of the methodologies and strategies used for market, SWOT and risk analyses, a description of the Project Breakdown Structure and the methodology for the cost analyses, as well as user-relevant information on the project's data management and 'Open Data'.

Contents

1 Introduction

Deliverable D7.1 is the preliminary version of a collection of documents that will be prepared in WP7 with the aim to support potential future users of the CompactLight technologies in the development and implementation of their projects and in their fundraising activities. It reflects the current state of the corresponding WP7 activities and represents thus a preliminary version of the final deliverable D7.2 of WP7. The documentation will be further developed and integrated during the last project year of CompactLight.

Section 2 of the document is dedicated to a landscape analysis of accelerator-based light sources in Europe, considering also the subscription rates for both, synchrotrons and free electron lasers. Case studies of users at the Italian facilities Elettra and FERMI are presented as a first insight into the European user communities.

Section 3 summarises the current state of the investigation into the requirements of the European scientific FEL users on the basis of existing scientific knowledge as well as a user survey, a user workshop, and other face-to-face discussion of the project partners with the user community.

In section 4, methodology and strategy for the market analysis, which is currently carried out by the Athens University of Economics and Business (AUEB), the third party of XLS working in collaboration with the Greek project partner IASA, are presented.

Information about the methodology and procedure that will be applied for the cost analyses of the CompactLight facility and for the cost comparison with currently existing infrastructures with similar performances are provided in Section 5. Also a general description of the Project Breakdown Structure (PBS) developed for the collection of the costing data is given.

Sections 6 and 7 provide first results from the SWOT analysis and the risk analysis that are under way in close collaboration with AUEB.

Finally, section 8 describes the data management and related policy of the CompactLight project, with a view to data and information that could be valuable for potential future users of the CompactLight technologies.
Each section includes a short outlook on planned activities and expected results for the last project year that will be integrated and complete the documentation for potential applicants of the CompactLight technologies in deliverable D7.2. The final collection of strategic documents will in particular also contain new sections, not yet present in deliverable D7.1, addressing the complementary application possibilities of the novel technologies and providing an overview of the developed technologies.

2 Landscape Analysis

2.1 Introduction

Since the first observation of synchrotron radiation at General Electric in 1947 [1] and the recognition of its exceptional properties in the following years, accelerator-based photon sources, such as synchrotron storage rings and, later on Free Electron Lasers, have developed into the most powerful tools for the research on matter. The scientific use of synchrotron radiation started in the 1960s with parasitic photo-ionisation experiments at the 180 MeV electron synchrotron of the National Bureau of Standards NBS in the USA [2] and other existing synchrotrons, among them the three European facilities operational at that time, Adone in Italy, Daresbury in the UK and DESY in Germany [3, 4]. Recognising the potential of the new light sources for experimental science, a new generation of synchrotrons, based on electron storage rings and dedicated to scientific users has been constructed and a wide spectrum of sophisticated experimental techniques has been created and adapted to research requirements in many different fields. Access to the highly brilliant radiation of accelerator-based light sources is meanwhile an essential prerequisite for research excellence in a large number of fields. From the very first beginnings, accelerator-based light sources have continuously been further developing to produce light with always superior characteristics. This has recently led in particular to the development of Free Electron Lasers, instruments producing highly brilliant radiation with unique characteristics that complement synchrotrons, offering completely new research opportunities [5–7]. However, currently FELs have extremely high costs and their possibilities for the accommodation of experimental stations are rather restricted. The following analysis of accelerator-based photon sources aims at exploring the landscape of currently existing user facilities and projects in relation to the users' access needs, to support decision-making on future requirements in terms of facility upgrades and construction of new machines.

2.2 The Landscape of European Photon Sources

A landscape analysis of European accelerator-based photon sources and related roadmaps has been recently published by the League of European Accelerator-based Photon Sources LEAPS [8]. According to this work, 14 storage ring based synchrotron light sources and 7 FEL facilities, all open for transnational users, are currently operated by 16 different institutions in Europe. CLIO, a very low energy FEL, is not a LEAPS member and therefore not listed in their table. These European light sources are located in 10 countries, provide more than 300 experimental stations with a large variety of measurement techniques, serve a continuously growing community of more than 24,000 users from all over the world, and many of them are today seriously oversubscribed [8, 9]. In the following, major results from the LEAPS analysis will be recapitulated.

2.2.1 Synchrotron Laboratories in Europe.

The list of the 14 European synchrotron laboratories, serving external users on the basis of an 'open access' policy, and their main features from [8] is provided in table 1. The facilities are listed in order of decreasing electron beam energy, since this attribute determines largely their spectral range of optimal performance and thus the type of research problems and experiments for which they are best suited. Usually, synchrotron light sources are therefore categorised according to their electron beam energies.

Facility	Site	Start User Operation	Energy (GeV)	Emittance (nm rad)	Beamlines		User	
					active	target	visits	projects
ESRF	Grenoble France	1994	6	4	48	50	9,024 (650)	1,258
PETRA III	Hamburg Germany	2010	6	1.2	20	27	4,300	700
ALBA	Barcelona Spain	2012	3	4.2	8	20	1,766 (197)	256
Diamond	Harwell UK	2007	3	2.7	28	33	10,437 (4,188)	2,623
MAX IV	Lund Sweden	2016	3	0.33	5	18		
SOLEIL	St. Aubin France	2008	2.75	3.9	29	-	4,138	687
SLS	Villigen Switzer-land	2001	2.4	5.5	16	-	3,134	1,037
Elettra	Trieste Italy	1993	2.0-2.4	7-10	25	-	1,320	510
BESSY II	Berlin Germany	1998	1.7	7	31	-	3,200	850
MAX IV	Lund Sweden	2017	1.5	6	3	8		
SOLARIS	Krakow Poland	2018	1.5	6	2	16		
ASTRID 2	Aarhus Denmark	2013	0.58	12	6	7	120	60
DAFNE	Rome Italy	2000	0.51	280	5	7	30	15
MLS	Berlin Germany	2008	0.1-0.63	100	7	-	90	25

Table 1: Synchrotron Laboratories in Europe. All data and information from [8]. Beamlines: number of beamlines that can work in parallel. User visits: individual user visits. User projects: approved proposals. Data refer to the last 1-year period with data available (see [8]).

The two hard X-ray machines, ESRF and PETRA III, with an electron beam energy of 6 GeV can deliver radiation with photon energies above 100 keV that can penetrate far inside hard condensed matter. The laboratories in the electron energy range of about 3 GeV are providing their optimum performance in the medium photon energy range at about 8-10 keV, which is particularly appropriate for structural investigations of matter with atomic resolution. The soft X-ray light sources in the lower part of the table with electron beam energies of 2 GeV and below are achieving their top performance in the VUV and soft X-ray range of the spectrum at photon energies of 10 eV - 1,500 eV and are thus ideal for exploring the electronic and magnetic structure and chemical properties of matter.

In each of these photon ranges, a large number of research questions can be approached, which is reflected in a large variety of possible experimental techniques and instrumental setups. Depending on the size of its storage ring, each synchrotron can however only accommodate a different, limited number of beamlines equipped with highly specialised experimental instrumentation that is suitable for a particular type of experiments. Since for synchrotrons with the same technical performances different selections of experimental techniques are possible, these synchrotrons can anyway offer quite different and even complementary research opportunities to the users.

According to the LEAPS analysis, the total number of beamlines at European facilities that can be operated simultaneously is 233, with a future target of nearly 300. The number of experimental stations is more than 300, due to the possibility to have more than one experimental setup at the same beamline or switch between different beamlines at the same light exit.

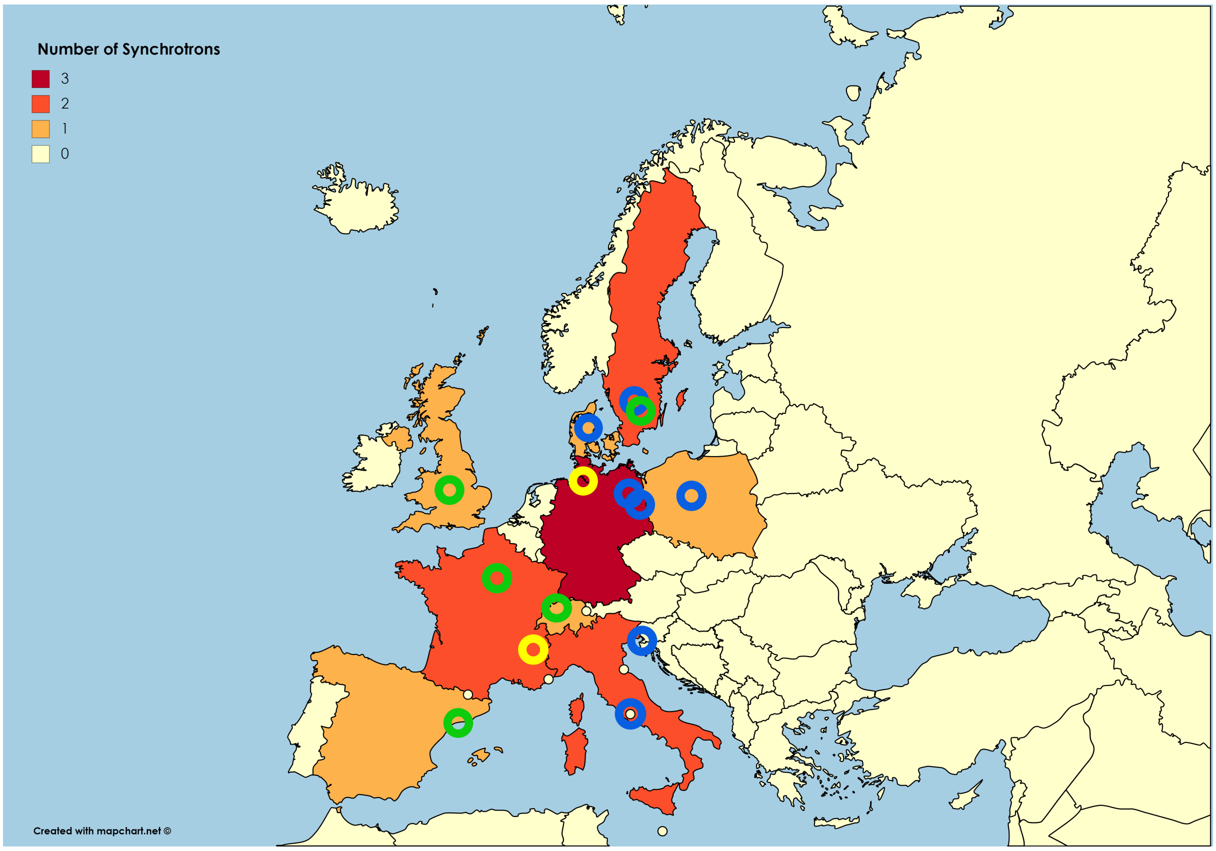


Figure 1: Locations of the European Synchrotrons. Yellow: hard X-rays, green: medium X-rays, blue: soft X-rays.

Figure 1 shows the location of the European synchrotrons. Germany is hosting three facilities, among them the hard X-ray laboratory PETRA III. Sweden and Italy have two synchrotron light sources optimised in the medium/soft X-ray spectrum, while France is operating a national medium X-ray laboratory and hosting the European hard X-ray facility ESRF. One synchrotron is running, respectively, in Switzerland and the United Kingdom (both medium X-ray) as well as in Denmark and Poland (both soft X-ray). Figure 1 reveals in particular, that almost the entire Eastern and Central European region is short of synchrotron facilities, with the only exception of Poland, where Solaris has started user operation in 2018 and is now ramping it up.

Some of the European facilities are meanwhile well advanced in years. For this reason, the Swedish synchrotron has been recently upgraded to MAX IV that offers two storage rings, the smaller one operating at 1.5 GeV and producing radiation in the VUV/soft-X-ray range, while the larger one, working at 3 GeV, is producing medium/hard X-rays. This ring, considered the first 4th generation storage ring worldwide, is based on the most advanced accelerator technologies. The novel multibend achromat lattice provides a strong focusing and leads to ultra-low emittance and the production of ultra-bright hard X-ray radiation [10–12]. The upgrade of MAX-lab to the MAX IV facilities has been completed in 2017 and user operation has just restarted. For this reason the LEAPS table does not contain user data for MAX IV yet.

The new Polish facility SOLARIS, based on the design of the 1.5 GeV ring of MAX IV [10], is open for users since 2018 and also in this case user data are therefore not yet available in the table.

The new MAX IV technology has subsequently been further developed by the ESRF and is employed for their new EBS (Extreme Brilliant Source) storage ring, which is to be 100 times more brilliant and coherent than the old one and is planned to become operational in 2020 [13].

A further facility upgrade towards higher brilliance and coherence is currently in course at Elettra (Elettra 2.0) [14] and other synchrotrons will enter now the planning phase.

2.2.2 Submitted and allocated Proposals at Synchrotrons.

Figure 2 shows the number of allocated proposals as a percentage of the proposals submitted by users at Elettra [15], ESRF [16], ALBA [17], and MAX IV [18] for the years 2013-2018 (as far as available). The allocation year labelling is however not handled in the same way by the diverse synchrotrons. It refers for instance to calendar years at ALBA and ESRF, for annual periods starting in July of the label year at Elettra, and to allocation periods starting in the end of the year of the call and extending well into the following year at MAX VI. Also, the numbers for MAX IV relate to the total for both rings.

After the facility upgrade at MAX-lab in 2016, user operation at the MAX IV laboratory has restarted in 2017. Proposal data are therefore only available for 2017 and 2018, and the average refers just to these first two years of operation. For the other laboratories data for several years are shown. The average relates to the years 2013-2017 for ALBA and to the period 2010-2018 for Elettra and ESRF.

The data show that the facilities can satisfy the user demands only partially. At Elettra, between

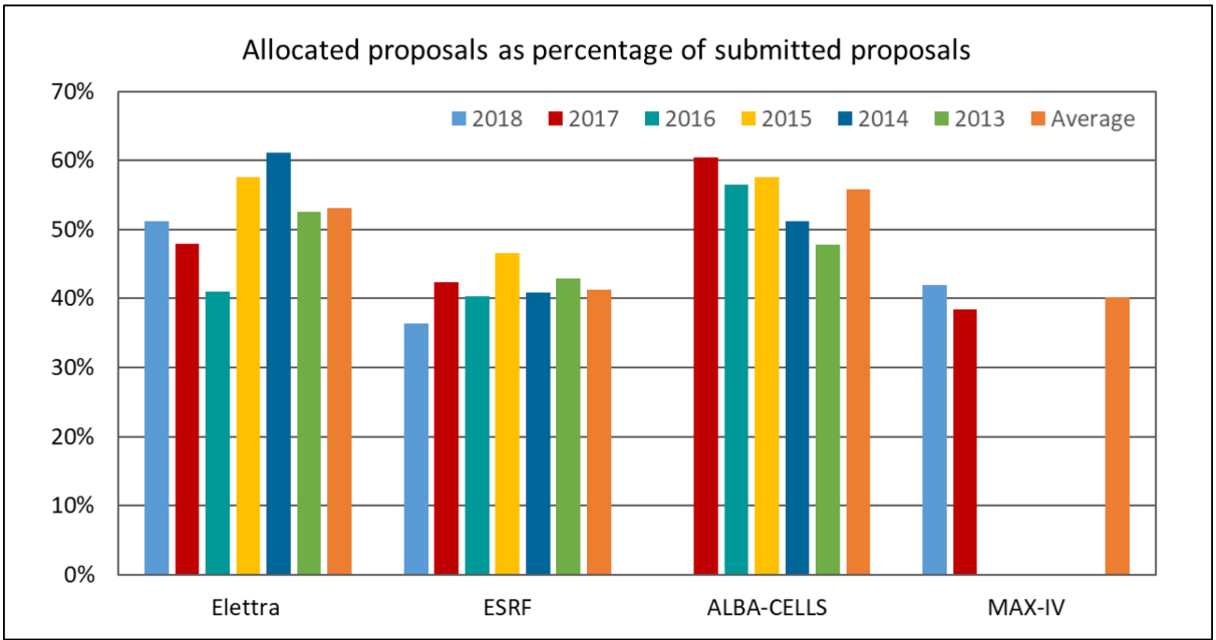


Figure 2: Proposals allocated in the years 2013-2018 and average over all available years at the European Synchrotrons Elettra [15], ESRF [16] ALBA [17] and MAX IV [18] as a percentage of the proposals submitted by the users.

41% and 61% of the received user proposals could be allocated during the last years, with an average of 53%. The numbers are quite similar at ALBA, with an average of 56% and smaller oscillation between 48% and 60%. At ESRF and MAX IV the oversubscription is higher and only about 40% of the user demands could be met, with variations between 36% and 47% at ESRF.

2.2.3 European Free Electron Lasers (FELs).

Table 2 gives a list of the currently operational Free Electron Lasers (FELs) in Europe. The information in this table stems from the LEAPs analysis [8]. FELs are accelerator-based photon sources that use a laser-like process to generate very intense, ultra-short and highly coherent radiation, with application opportunities for users that are complementary to those of synchrotrons. Very low energy FELs creating infrared and THz radiation, such as FELIX and CLIO, have been open for external users since the early '90. FELs producing X-rays have become available only in 2005, when the first VUV/soft X-ray FEL FLASH started user operation in Hamburg (DE). FERMI, the second FEL operating in the VUV/soft-X-ray range has been opened for users in 2012 in Triest (IT). Subsequently, also two hard X-ray facilities have been constructed and are now open for user operation, namely the European XFEL (since 2017) in Hamburg (DE) and the SwissFEL (since 2018) in Villigen (CH).

The geographic distribution of the European FEL sources is shown in figure 3. The MAX IV FEL in Lund, indicated in the figure, is not yet in operation. The figure reveals that the few FELs currently available for external users are concentrated in the Western part of continental Europe. In particular, despite their huge importance for materials research, X-ray FELs already open for users exist only in Germany, Switzerland, and Italy. The MAV IV FEL in Lund

(Sweden) is at the moment the only confirmed project that will provide supplementary research opportunities with FEL radiation in the near future.

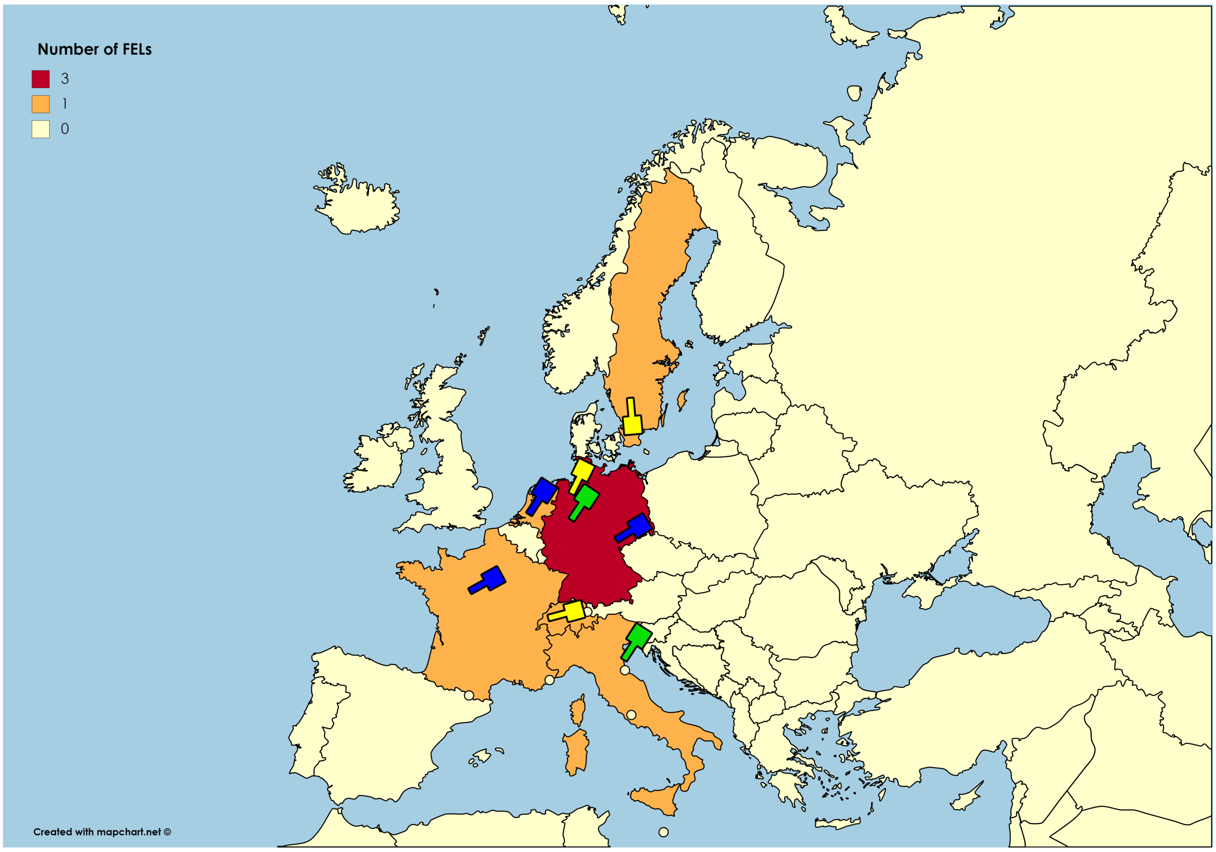


Figure 3: Locations of the European Free Electron Lasers. Yellow: hard X-rays, green: soft X-rays, blue: THz/Infrared.

2.2.4 Submitted and allocated Proposals at FELs.

In figure 4, the number of allocated proposals as a percentage of the proposals submitted by FEL users at FERMI [20], European XFEL [21], and SwissFEL [22, 23] for beamtime allocation in the years 2017-2019 is depicted. It is to be noted that the beamtime allocation periods are different for each laboratory and do not necessarily coincide with the calendar year. The year in the diagram is therefore only indicatively, which does however not affect the discussion. Due to the recent start of user operation, in the case of the SwissFEL data are only available for the first allocation period 2019 covered by the first call for proposals closing in autumn 2018. The illustrated average equals therefore the data for 2019, while for the EU XFEL it refers to the years 2017-2019 (run 1 - run 3) and for FERMI to the period 2013-2019 (call 1 - call 7).

It is evident from the diagram that the currently operating facilities can satisfy the user demands only partially. At FERMI, in average 34% of the beamtime requests could be allocated in the period 2013-2019, with numbers varying between 28% and 35% in the last years. A slightly higher percentage of 44% has been observed for the first two calls for proposals, when the community was still starting to evolve. At the European XFEL the average over the last three years is below 25%, fluctuating between 20% in 2018 and 27% in 2019. At SwissFEL, only 14% of the submitted proposals of the first call could receive beamtime.

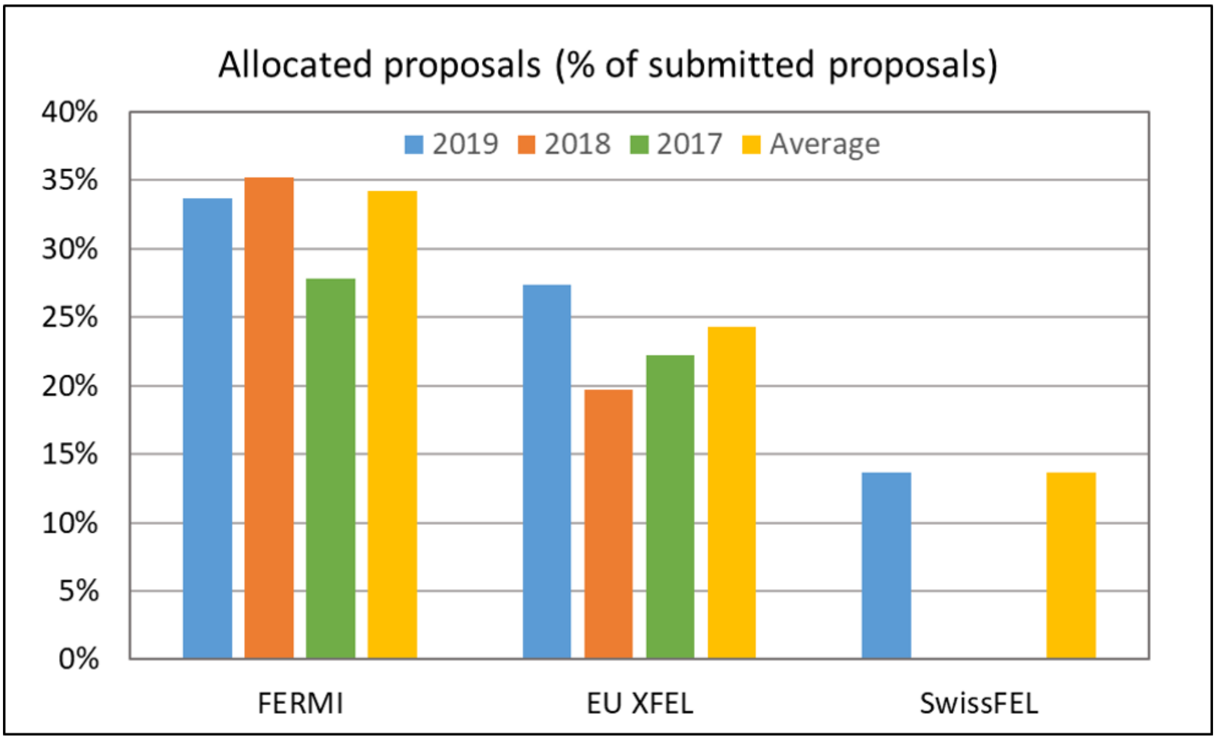


Figure 4: Proposals allocated in the years 2017-2019 and average over all available years at the European FEL sources FERMI [20], European XFEL [21], and SwissFEL [22, 23] as a percentage of the proposals submitted by the users.

Based only on the data of the latest call of each facility (labelled 2019), the demand from the presently active user community can be met by roughly 25%. Considering, that X-ray FELs are still a very young type of research infrastructure and that their user communities have just started to develop, the number of potential users can be assumed substantially higher than those applying for beamtime today. Face-to-face discussions with interested users of light sources who have not used FELs so far suggest also, that many of them are currently not submitting applications due to the low success probabilities. In addition, the past experience with the synchrotrons indicate that the development of user communities is largely facilitated by the presence of accessible infrastructures in their vicinity, which means that the large 'white areas' without FELs in Europe obstacle the consolidation of national user communities in many, and especially Eastern European countries.

In order to evidence the increase of the demand for beamtime by the FEL user community, figure 5 shows the number of submitted proposals at FERMI for all hitherto existing calls (call 1 - call 7), which refer to the complete period of user operation (2013 - 2019).

The figure demonstrates a continuously increasing demand from the users, a persisting trend from the start of user operation that is obviously not attenuating yet. In particular, the demand has triplicated from 32 in 2013 to 98 in 2019, indicating the development of the FEL user community and the evolution of the user skills.

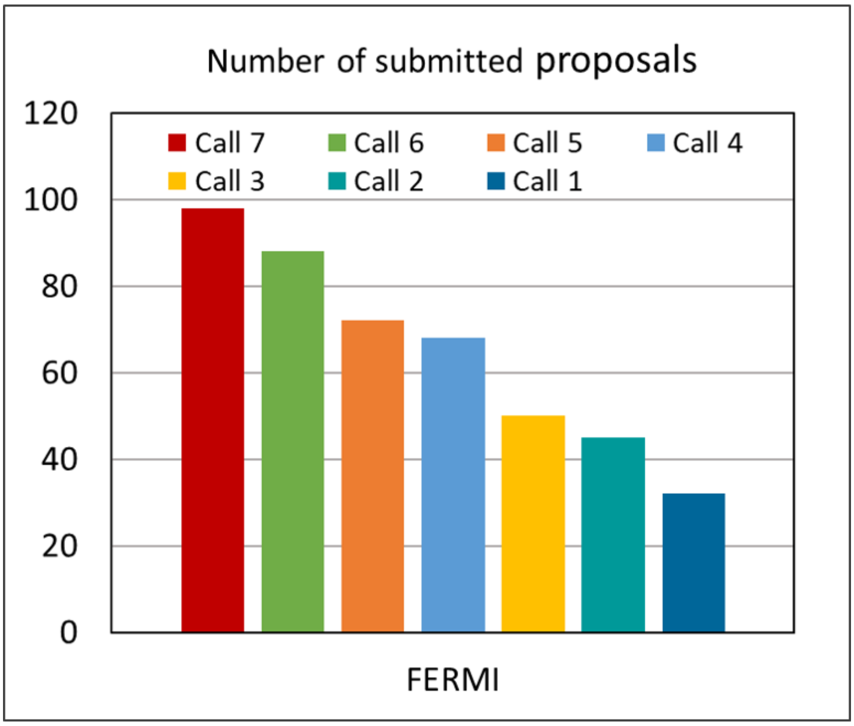


Figure 5: Submitted proposals for beamtime at FERMI for the whole user operation period by call (data from [20]).

Facility	FEL-lines operating in parallel	Experim. Stations	Site	Users since	Energy (GeV)	Photon Energy	Pulse prop.
EU XFEL	SASE-1	2	Hamburg (DE)	2017	8.5 - 17.5	(3.0-20) keV	(1-100) fs 10*2,700 pulses/s
	SASE-2	2		2018			
	SASE-3	2		2018			
SwissFEL	AMARIS	3	Villigen (CH)	2019	2.1-5.8	(1.8-12.4) keV	(2-40) fs 100 Hz
	ATHOS	3		2020		(0.24-1.93) keV	
MAX IV	FemtoMAX	3	Lund (SE)		3.0	(1.8-20) keV	100 fs 100 Hz
FERMI (Seeded)	FEL-1	6	Trieste (IT)	2012	1.5	(15-90) eV	(20-90) fs (10-50) Hz
	FEL-2			2016		(65-310) eV	
FLASH	FLASH-1	5	Hamburg (DE)	2005	0.4-1.25	(26-300) eV	10-300 fs to 10*800 pulses/s
	FLASH-2	2		2016		(14-400) eV	
ELBE	FELBE	7	Dresden (DE)	2005	0.015-0.040	(5-240) meV	(0.5-30) ps 13 MHz cw
	TELBE	1		2016		(0.5-10) meV	also 100 kHz cw
FELIX	FELIX 1/2	12	Nijmegen (NL)	1993	0.015-0.050	(8-400) meV	(0.5-10) ps 1 GHz, 25 MHz, 20 Hz
	FELICE	2		2007		(12-250) meV	(0.5-10) ps 1 GHz, 16 MHz, 20 Hz
	FLARE	4		2013	0.010-0.016	(0.8-12) meV	(10-80) ps 3 GHz, 20 MHz, 20 Hz
CLIO	CLIO	5	Orsay (FR)	1992	0.010-0.045	(0.25-8.3) meV	(1-10) ps 25 Hz

Table 2: FEL Facilities in Europe. Data and information from [8], except for CLIO. Information on CLIO from the CLIO Website [19]. MAX IV and the ATHOS FEL line at SwissFEL are still under construction. (see [8]).

2.3 Users of European Photon Sources

2.3.1 The European Photon Source User Communities

A strong and consolidated user community of photon sources has meanwhile developed in Europe, notebly promoted in the last decade also by the transnational access programme of the European Commission through dedicated projects in FP7 and H2020, such as ELISA, CALIPSO, CALIPSOplus, BIOSTRUCT-X, or NFFA [24]. The number of 24,000 users in Europe stems from a User Survey performed in 2012 by the FP7 project PanDataODI [25]. According to the European Synchrotron and FEL User Organisation (ESUO), a cooperation of European national user organisations, the number of users in the 30 countries (including Turkey and Israel) represented by ESUO has meanwhile increased to more than 30,000 [25]. The map of the ESUO member countries in figure 6 shows that in nearly all Western, Central and Northern European and many South-East European countries have been established organisations representing the national users of photon sources. This implies in particular, that user communities interested in collaboration and exchange are existing nearly all over Europe. A lack of coverage is currently observed mostly for the Balkans South-East of Croatia (Serbia, Kosovo, Albania, Montenegro, Bosnia-Herzegovina, and North Macedonia), as well as the Eastern European countries Romania, Moldova, Ukraine, and Belarus.

It may be assumed that the largest part of these users are performing their research at synchrotron laboratories that have, as explained above, a long history in Europe and that only a minority is using FEL sources at the moment. Moreover, the total number of beamlines, which can work in parallel at synchrotrons sum up to 233, in contrast to 13 FEL lines operating in parallel according to LEAPS [8]. At the moment it is rather difficult to estimate the size of the FEL community in Europe, since surveys have not been performed and user data from European facilities have hardly been published so far. Since FELs are still a young technology, user operation of most FEL facilities has only started in recent years, and not all their FEL lines are already operational, the FEL community in Europe is still expected to grow considerably in the future. this is supported by the trend observed for FERMI and discussed in 2.2.4.

For further insights into the community and the factors influencing its development, a couple of case studies on users of the Italian light sources Elettra and FERMI are presented in the following.

2.3.2 Case Study 1: European Users at the Italian Synchrotron Elettra

A deeper analysis of statistical data on users at the Italian synchrotron laboratory Elettra [15] confirms a consolidated presence of users from all over Europe during the last 10 years. The total number of users from Europe and a few adjacent countries is depicted in Figure 7 according to the indicated colour code. The largest user community at Elettra has clearly been, with 3,874 users in the considered period, the Italian one. Italian researchers account for 41% of the European and 35% of all users. A large number of users has also been observed from the big European countries Germany (1089 users), France (837 users), United Kingdom (525 users) and Spain (355 users), which are operating own national laboratories and, in the case of France, the European Synchrotron Radiation Facility ESRF, and which have therefore sci-

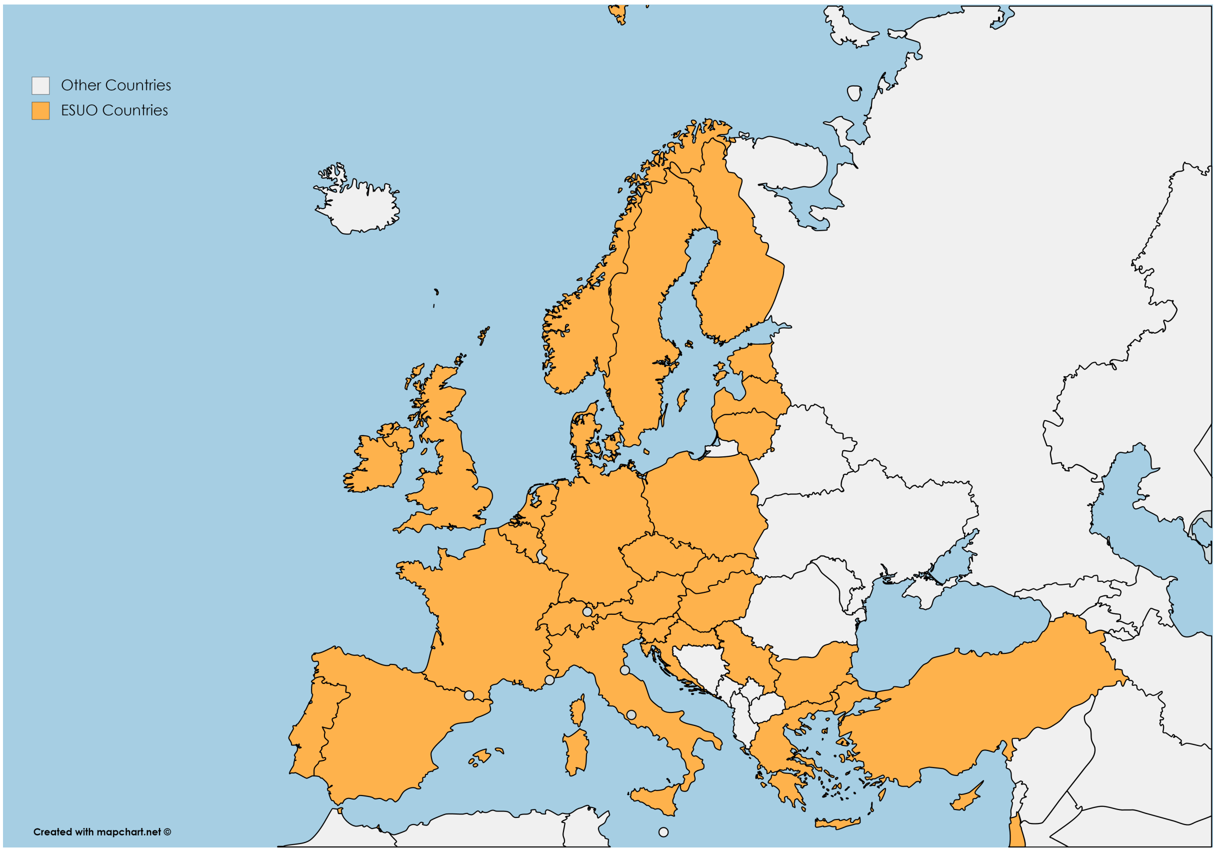


Figure 6: Map of ESUO Member Countries (in orange).

entific communities with large expertise in the relevant fields. Their usage of Elettra through transnational access might indicate that they collaborate with local research teams or that the opportunities offered by their own facility do not satisfy all their demands. In the latter case this may be related to the particular beam characteristics or specific experimental methods and equipment available at FERMI, since each FEL can offer only a limited number of beamlines and measurement setups.

Less, but still considerable users are coming to Elettra from the smaller European countries with own light sources, Switzerland (188 users), Sweden (230 users), and Denmark (123 users). The scientists in these countries benefit from existing know-how, possibilities of skill development, and research opportunities offered by the presence of a light source in their own country and are probably specialised in the research methods offered by their own facilities. Also, due to the limited size of their national communities, user numbers are in general expected to be lower, so that the facilities can probably already satisfy the national demands to a large extent.

For Poland, which has recently started user operation at the new national synchrotron laboratory Solaris, the user numbers at Elettra have increased after 2013, indicating that the Solaris project has pushed interest, skill development, and demand of the Polish scientific community, while they were looking forward to their own light source.

Closer attention are deserving Austria (381 users), Czech Republic (282 users), Croatia (252

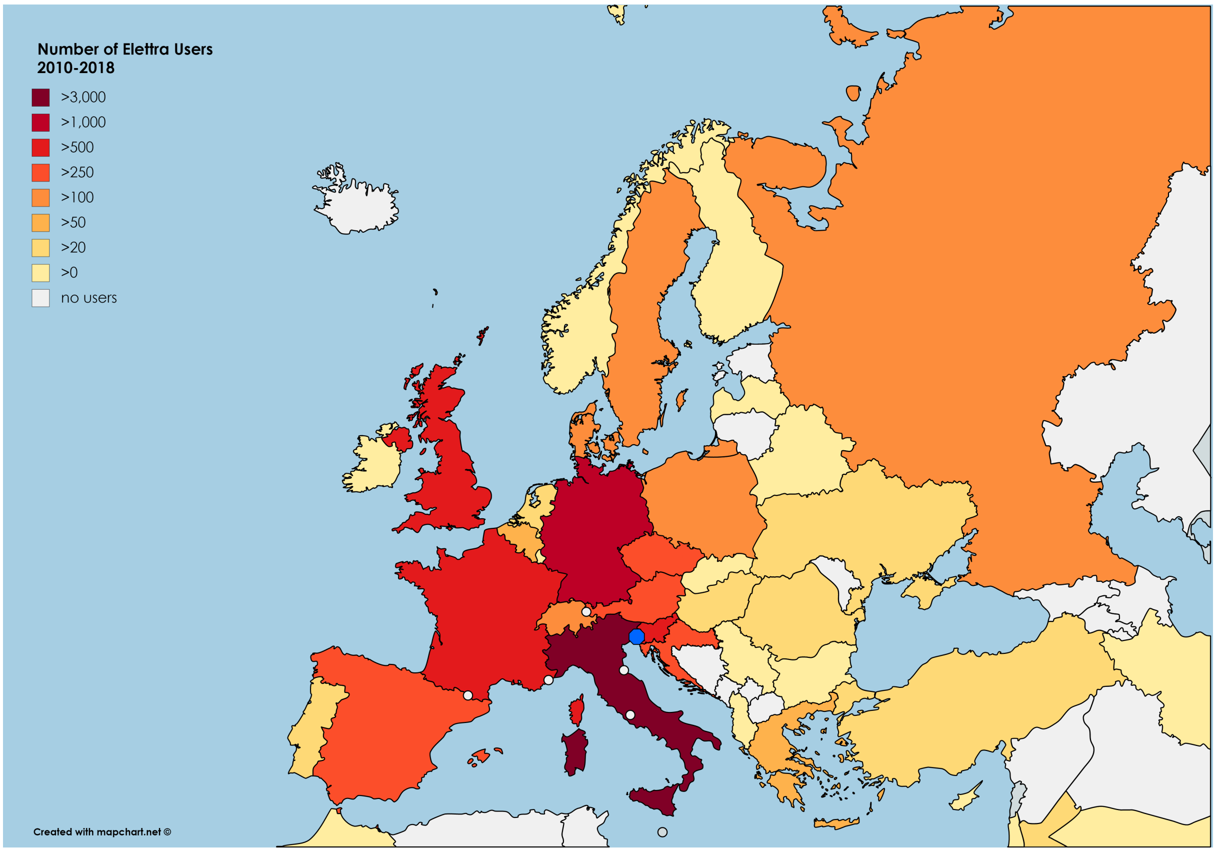


Figure 7: Countries of origin of Elettra users by number of users in the years 2010-2018; the colour graduations correspond to >3,000 (dark red), > 1,000, >500, >250, >100, >50, >20, >0, and no users (white); the position of the Elettra synchrotron laboratory is indicated by the blue spot. Data from [15].

users), and Slovenia (518 users), partner countries of Elettra Sincrotrone Trieste without own national light source and of limited size, but with a huge number of scientists, as compared to their small populations, using the synchrotron Elettra. The development of these user communities has been achieved through a long lasting cooperation based on formal bilateral agreements and their implementation by the scientists in the form of tight research collaborations. In the cases of Austria and the Czech Republic, these have been fostered by the construction of an Austrian beamline (SAXS) and a Czech beamline (Material Science) at the synchrotron Elettra and the settling of permanent research groups from these countries on the premises of Elettra Sincrotrone Trieste, while in the cases of Slovenia and Croatia the location of Elettra on the Slovenian border and thus nearby to major research centres of these partner countries plays an important rule.

The most apparent European region without or with very few users at Elettra are, despite their relative proximity and consistent with the observations made for the ESUO coverage, the Balkans (Serbia, Kosovo, Albania, Montenegro, Bosnia-Herzegovina, and North Macedonia), but also most Central and Eastern European countries (Bulgaria, Romania, Hungary, Slovakia, Moldova, Ukraine, Belarus, Latvia, Lithuania and Estonia).

It should however in all cases be kept in mind that users might also prefer, for logistic or scientific reasons, to work in other European facilities. This is probably the case for users at the Western (Portugal, Ireland) or Northern (Norway, Finland) boundaries of Europe. For Northern Europe this is confirmed by the data from the MAX IV laboratory [18] shown in figure 8, which highlight that, apart from 50% of Swedish users, a large fraction of their users are from other Northern countries (Denmark: 16%; Norway: 5%; Finland: 4%; Baltic countries: 4%).

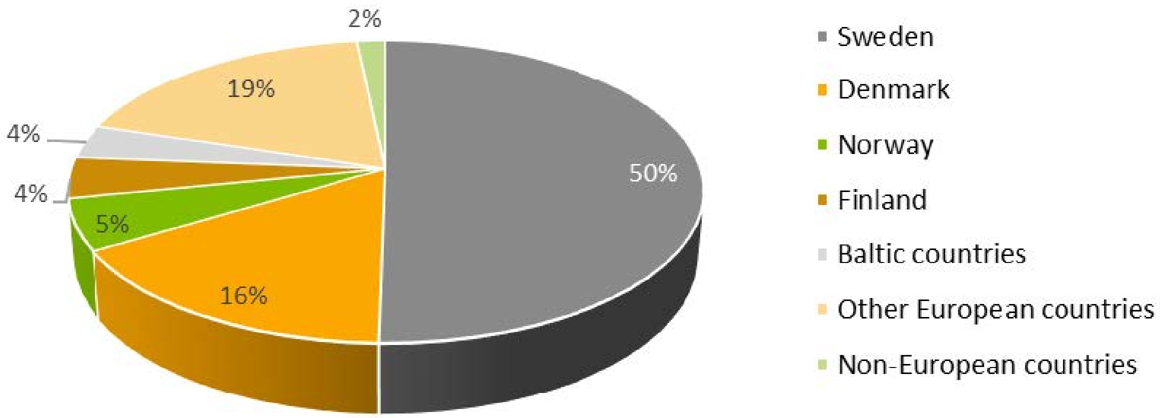


Figure 8: Countries of origin of MAX IV users 2018. Figure from [18].

A more complete picture requires user data from more European light sources to be included in the analysis, a work planned for the next months.

2.3.3 Case Study 2: Non-European Users at the Italian Synchrotron Elettra

European facilities are not only serving the European users; they are attracting also a number of users from other continents [15]. The data illustrated in figure 9 show that between 2010 and 2018, 86% of Elettra's users have been from European institutions (9423 users), while 9% have come from Asia (992 users), 3% from the Americas (380 users), and less than 1% from each Africa (57 users) and Australia & New Zealand (83 users).

In the latter case, the large majority has been from Australia (79 users), see figure 10, where users are also served by a national Australian Synchrotron facility and the collaboration with Elettra is facilitated by formal agreements at the political as well as institutional level.

African users do not benefit from any light source in their continent until now, which renders it difficult for them to gain experience and develop skills. Without experience, proposal applications at facilities in other continents have a low probability of success and moreover, a possible beamtime allocation entails high costs in terms of time, money and effort for these users. This

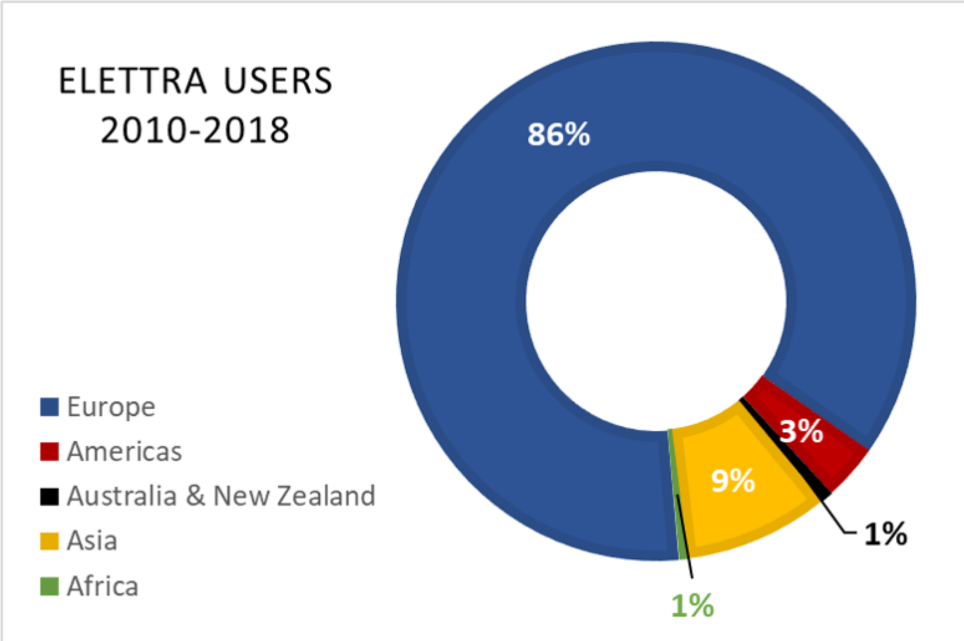


Figure 9: Percentage of Elettra users 2010-2018 by continent. Data from [15].

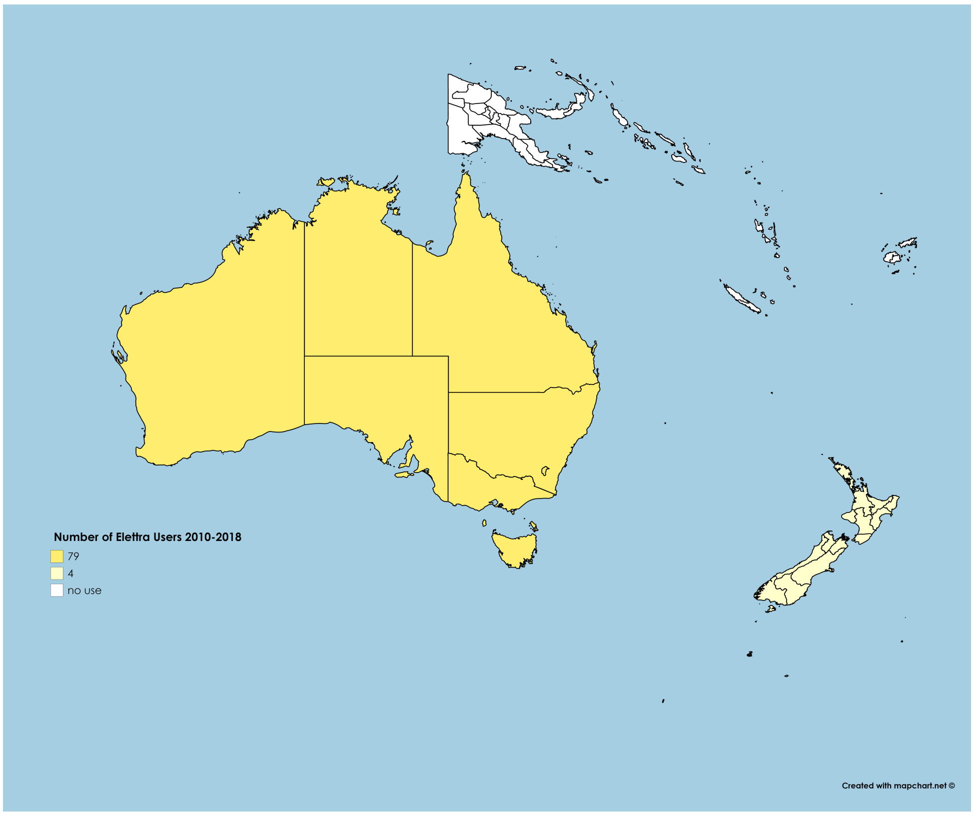


Figure 10: Countries of origin of Elettra users from Australia & New Zealand by number of users in the years 2010-2018; the colour graduations correspond to 79 (dark yellow, Australia), 4 (light yellow, New Zealand), and no users (white, other countries). Data from [15].

hinders the creation of consolidated user communities in African countries. A small number of 57 users from Africa has anyway carried out experiments at Elettra in the period 2010-2018. As shown in figure 11, three quarter of them (42 users) have been, despite the large distance, from South Africa, as the result of a long-term collaboration with a research group there. 21% have come from Egypt (12 users, involved in the SESAME project, see below) and very few from other countries (Cameroon: 2 users, Morocco: 1 user).

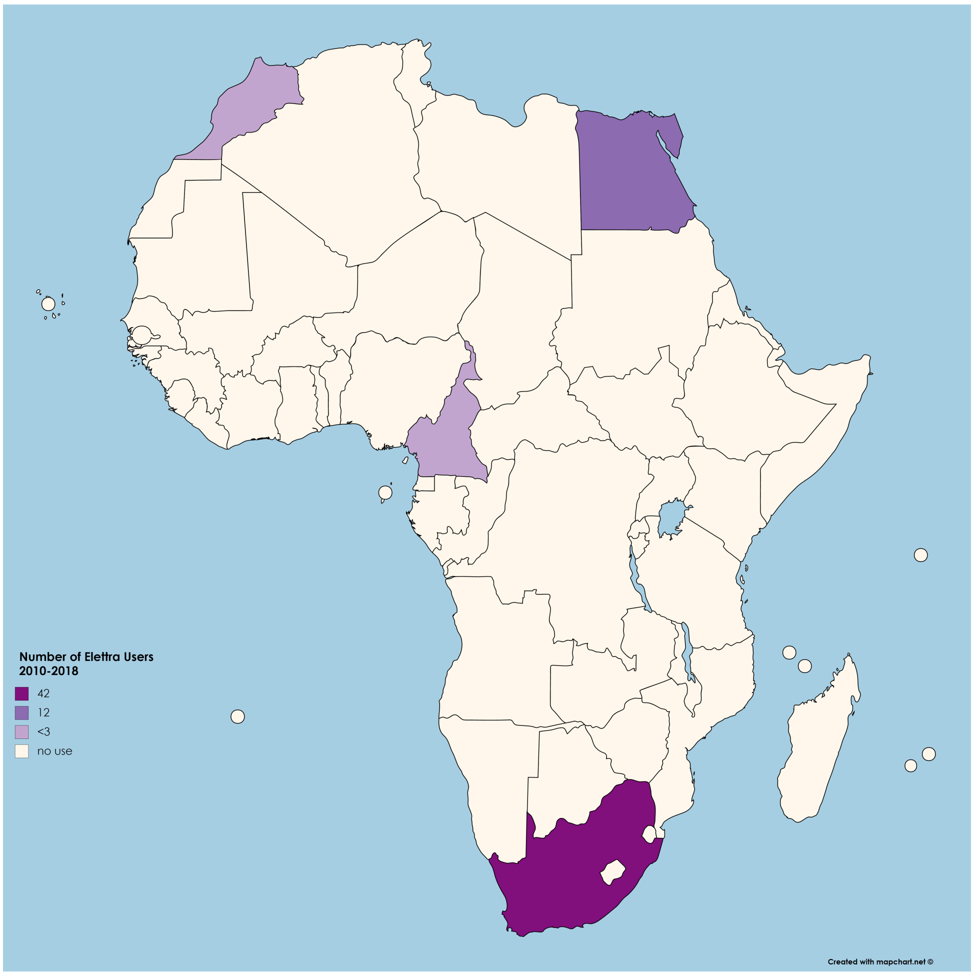


Figure 11: Countries of origin of Elettra users from Africa by number of users in the years 2010-2018; the colour graduations correspond to 42 (dark violet, South Africa), 12 (violet, Egypt), <3 (light violet, Morocco, Cameroon). and no users (white, other countries). Data from [15].

50% of the researchers from the Americas who have used Elettra in the years 2010-2018 have been from the United States (189 users), 17% from Canada, and 12% from Mexico (44 users) and Brazil (42 users), as illustrated in figure 12. Three of these countries dispose of own national facilities, while the Mexican community might benefit for the development of expertise from their proximity to the North American facilities. Further users have arrived from Argentina (24 users), Cuba (16 users), Chile (1 user), and Peru (1 user).

The largest quota of non-European users at Elettra in 2010-2018 has been from Asia, as shown in figure 13, with 56% of them coming from India (554 users). This is clearly fostered by

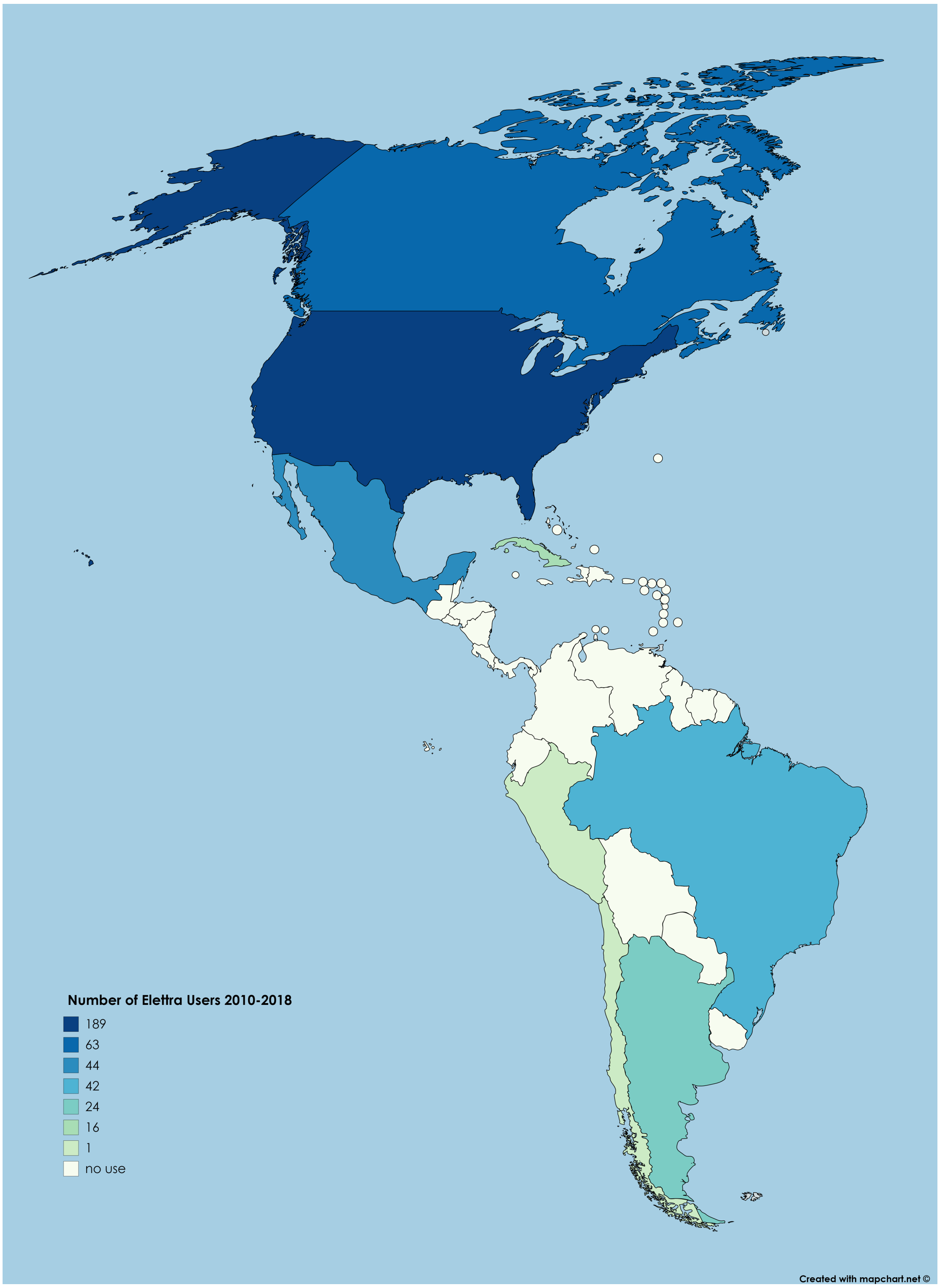


Figure 12: Countries of origin of Elettra users from the Americas by number of users in the years 2010-2018; the colour graduations correspond to 189 (dark blue, United States), 63 (Canada), 44 (Mexico), 42 (Brazil), 24 (Argentina), 16 (Cuba), 1 (Chile, Peru) and no users (white, other countries). Data from [15].

a long-lasting intense cooperation with the Indian Institute of Science in Bangalore, which culminated in the construction and joint operation of the XRD2 and Xpress beamlines at Elettra.

Noticeable numbers of user have also been received from Japan (13%, 128 users), China (10%, 101 users), Pakistan (7%, 73 users), and Israel (4%, 40 users), while smaller numbers have been observed from several other countries (Jordan: 24 users, Taiwan: 17 users, Iran: 11 users, Indonesia: 9 users, Thailand: 9 users, Singapore: 7 users, Republic of Korea: 5 users, Sri Lanka: 5 users, Hong Kong: 3 users, Oman: 2 users, Qatar: 2 users, Saudi Arabia: 1 user, United Arab Emirates: 1 user). Among the Asian countries, China, India, Japan, Republic of Korea, Singapore, Taiwan, and Thailand are operating national Synchrotron laboratories (see: https://lightsources.org/lightsources-of-the-world/asia-oceania/. The Middle East synchrotron SESAME in Jordan, which has recently started and is now ramping up user operation, is an international, transcontinental collaboration between Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, Palestine, and Turkey.

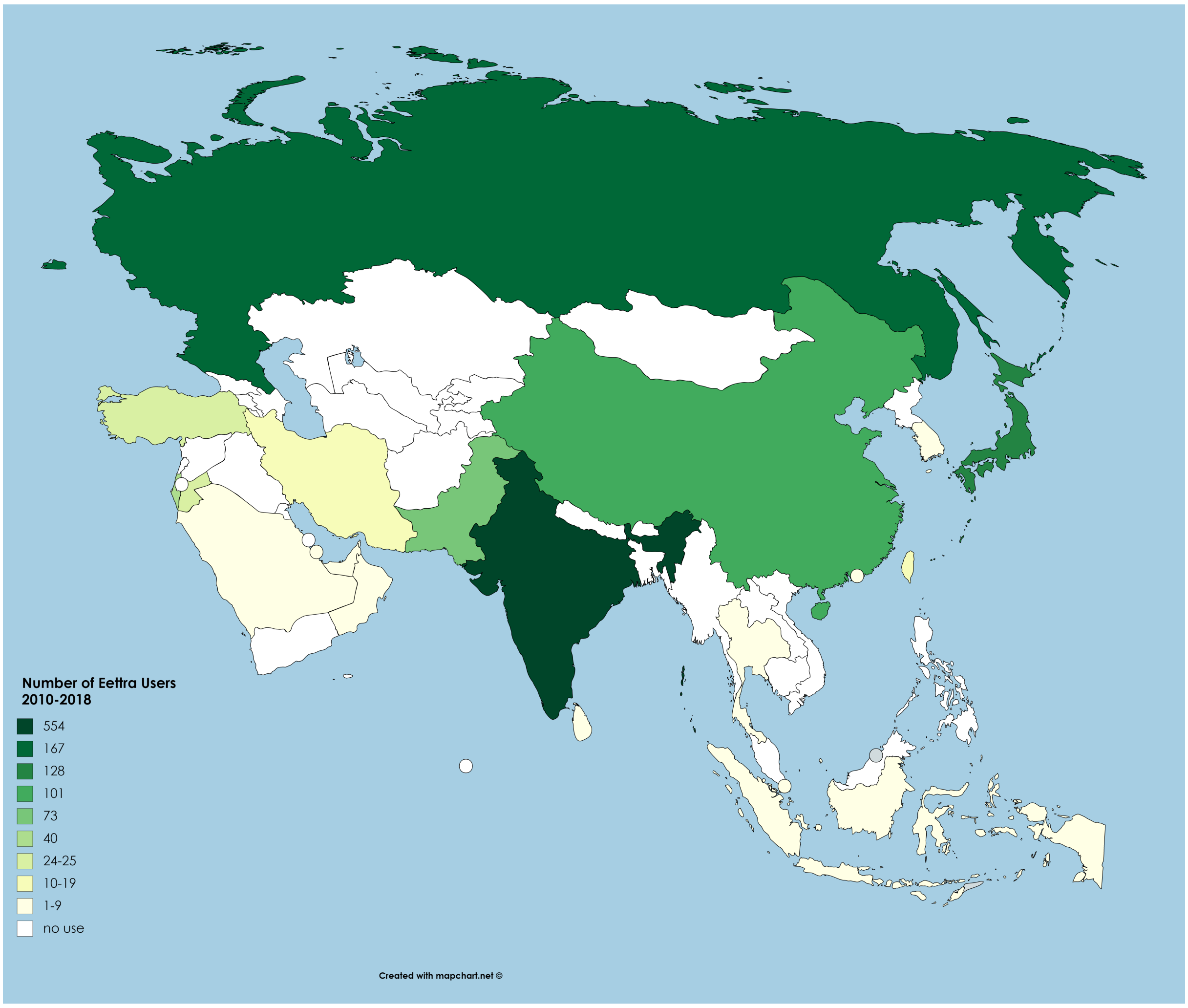


Figure 13: Countries of origin of Elettra users from Asia by number of users in the years 2010-2018; the colour graduations correspond to 554 (India), 167 (Russia), 128 (Japan), 101 (China), 73 (Pakistan), 40 (Israel), 24-25 (Turkey, Jordan), 10-19 (Taiwan, Iran), 1-9 (Indonesia, Thailand, Singapore, Sri Lanka, Republic of Korea, Hong Kong, Qatar, Oman, Saudi Arabia, Emirates) and no users (white, other countries). Data from [15].

2.3.4 CASE STUDY 3: PROPOSALS AND USERS AT THE ITALIAN SOFT-XRAY FEL FERMI

For the first years of operation of FERMI 2012-2017, statistical data have only been collected and published for the proposals that received beamtime. In this period, 90% of the allocated proposals have come from European users (100 proposals), 5% from US-based users (5 proposals) and 5% from Japanese users (5 proposals). The European proposals have been prevalently from Italy (42) and Germany (36), and to a smaller extend from Sweden (8), France (7), Switzerland (4), Slovenia (1), the United Kingdom (1), and the Netherlands (1) [20]. Except for Slovenia, all these countries, the United States and Japan included, are operating own FEL facilities, have communities pushing national FEL projects, or are member countries of the European XFEL, which underlines again the importance of a national/regional involvement for the development of expertise in the field of accelerator-based light sources.

This is confirmed by the first data on FERMI users, referring to the year 2018, which have just been published [20] and are analysed below. Figure 14 shows that the large majority of the FERMI users 2018, namely 88% (182 of 206 users) have been European, 8% American (USA: 13, Canada: 3), roughly 3% Asian (Japan: 6, Singapore: 1), and less than 1% Australian (1 user). No users from South America or Africa have been involved and the non - European users have been prevalently from the United States and Japan, where own FEL sources are available.

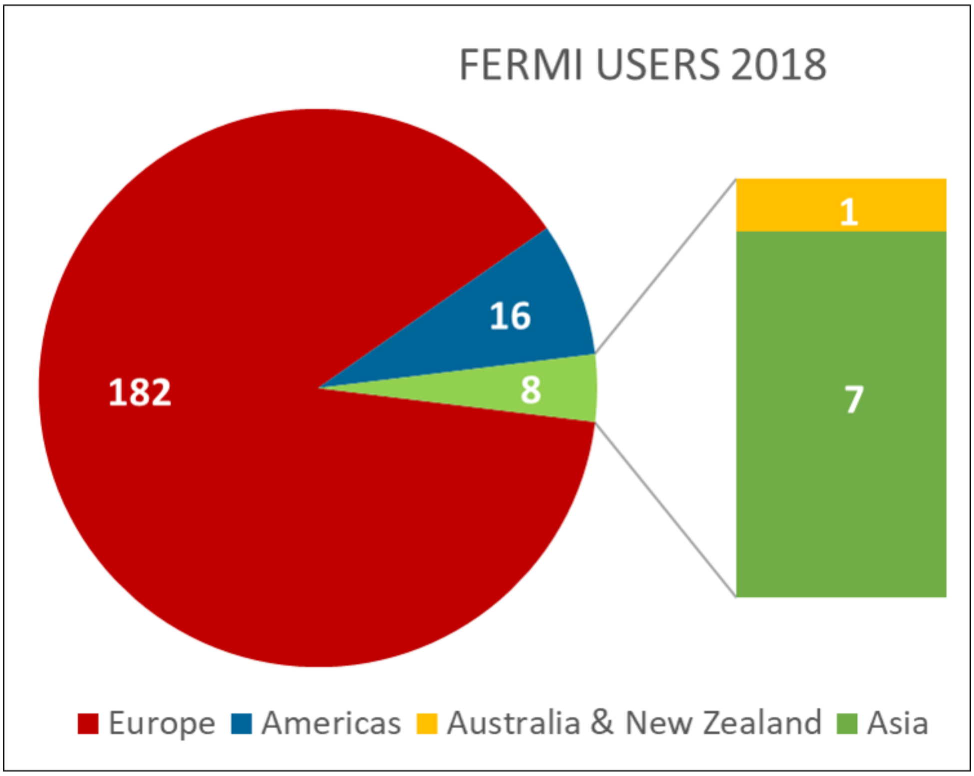


Figure 14: Percentage of Fermi users 2018 by continent. Data from [20].

Figure 15 depicts the provenience of the European FERMI users 2018. The by far largest number (42%, 76 users) have been users from Germany, where due to the three FEL facilities

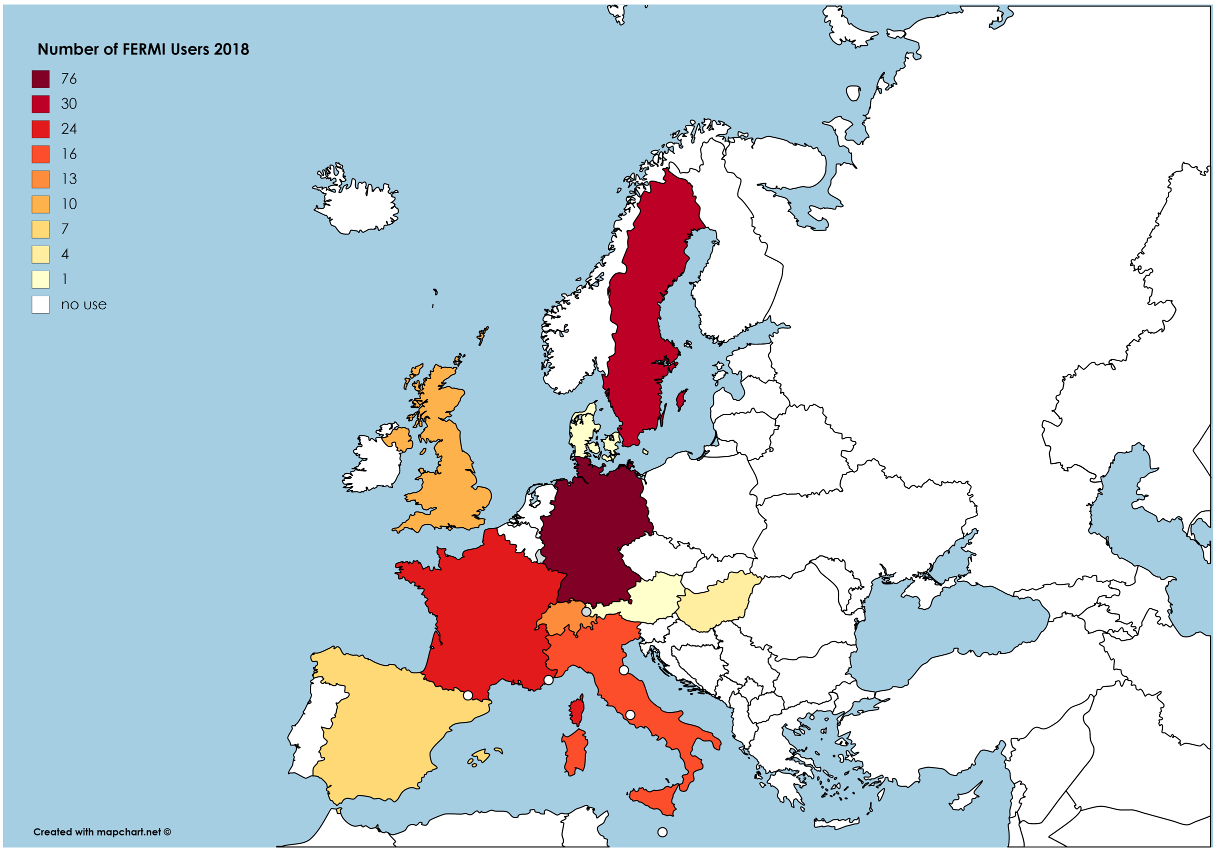


Figure 15: Countries of origin of European FERMI users by number of users in the year 2018; the colour graduations correspond to 76 (Germany), 30 (Sweden), 24 (France), 16 (Italy), 13 (Switzerland), 10 (United Kingdom), 7 (Spain), 4 (Hungary), 1 (Denmark, Austria) and no users (white, other countries). Data from [20].

FELBE, FLASH and European XFEL huge expertise is concentrated. Further contributions come from Sweden (30 users, MAX IV FEL project), France (24 users, hosting CLIO), Italy (16 users, hosting FERMI and the test facility SPARC), Switzerland (13 users, hosting SwissFEL), United Kingdom (10 users, hosting the test facilities ALICE and CLARA), Spain (7 users, EU XFEL partner), Hungary (4 users), Austria and Denmark (1 user each). Except for Austria, all these countries are involved in the European XFEL and most of them have highly experienced light sources user communities, since they are also running own synchrotron laboratories.

2.4 Outlook

For the final deliverable D7.2 of WP7, the landscape analysis will be integrated with data on non-European synchrotrons and FEL facilities and, if possible, with case studies on users from other European laboratories. An attempt to gather information on existing projects for new facilities or facility upgrades will also be made.

3 User Requirements

3.1 Introduction

A multitude of large-scale accelerator-based research infrastructures is today at the disposal of scientists in Europe, building the future in key areas of research and development for the next decades [26]. In particular, Synchrotron Radiation (SR) has become a fundamental and indispensable tool for studying matter, as shown by the large number of facilities in operation in Europe (see 2) and worldwide, which serve many users every year. The impact of SR across many disciplines cannot be doubted, as evidenced by the five Nobel prizes that have been awarded in the past twenty years to scientists, who have conducted research that has been made possible by SR [2].

For the beamlines of these facilities, which render the generated radiation usable for the experiments, the main figure of merit is the brightness, which defines the intensity of radiation, within a given bandwidth around the desired wavelength, focused onto a sample of given area, within a particular solid angle.

In the last decade, new photon sources, single pass FELs based on linear accelerators, successfully entered into operation. They can produce extremely high brightness and transversely coherent radiation, with many orders of magnitude enhancement in brightness over ring-based X-ray sources, pulse duration down to a few femtoseconds, broad wavelength tunability, polarization control and multi-color operation. Nowadays, they are becoming fundamental tools for a wide range of scientific and technological fields and have an important impact and innovation potential for the scientific community.

However, despite their potential and the huge user demand for beamtime (see 2.2.4), the number of FELs is currently very limited, particularly in Europe (see 3), as a direct consequence of their high costs and complexity.

To overcome this limitation and promote their diffusion, the CompactLight Collaboration intends to design an X-ray FEL facility beyond today's state of the art, using the latest concepts for bright electron photo-injectors, high-gradient X-band structures (operating at 12 GHz), and innovative short-period undulators. The resulting facility will benefit from a lower electron beam energy than current facilities, will be significantly more compact, with a reduced footprint, and will have a much lower electrical power consumption compared with current facilities. These ambitious, but realistic aims will result in much lower construction and running costs, making X-ray FELs more affordable, enabling the widespread distribution of such sources and expanding opportunities to utilize them.

To achieve these objectives, it is extremely important that the specifications of such an innovative, compact and cost effective FEL facility are driven by the demands of potential users and the associated science cases. To collect the user requirements on a time scale of 5-10 years, the CompactLight collaboration has undertaken several initiatives, culminating in a

[2]These five Nobel Prizes, based on research with SR, have been awarded in 1997 (Sir John Walker; SRS), 2003 (P. Agre and R. MacKinnon; CHESS), 2006 (Roger Kornberg; SSRL), 2009 (Venkatraman Ramakrishnan, Thomas A Steitz and Ada E Yonath; NSLS, APS and ESRF), and 2012 (B. Kobilka; APS and ESRF).

dedicated CompactLight User Workshop that has been held at the European Organisation for Nuclear Research (CERN) from 27 to 28 of November 2018. CompactLight representatives have also attended the Science@FELs Conference in Stockholm, Sweden (June 2018) and the Attosecond and FEL Science Conference in London, UK (July 2018) to hear about the latest scientific achievements using FEL and to informally interact with leading researchers to gather their views on the parameters and performance of future FELs.

In addition, a specially developed questionnaire has been sent to over 50 FEL experts within Europe, to collect the photon characteristics required by their current and future experiments.

3.2 Science requirements on a next-generation FEL

The table in figure 16 links the main scientific areas of FEL applications with the key parameters of the FEL radiation requested [27].

The request trends towards shorter pulse duration, in the tens of fs regime, with high peak brightness and laser-pump / FEL-probe applications are quite evident.

These trends have been also recently reviewed and confirmed by a group of users from around 20 Universities and National Laboratories worldwide [28]. Figures 17 and 18 graphically report the photon requirements for the different applications as elaborated by these users.

Furthermore, the requests for next-generation FELs collected in informal discussions with users at the 'Science@FELs' Conference in Stockholm (June 2018) and in the 'Attosecond and FEL Science' Conference in London (July 2018) fully support the data presented in the figures. In addition, during the discussions in these conferences and during the CompactLight User Workshop also a strong request for improving the coherence and stability properties of FEL radiation pulses as well as much better synchronization to external laser sources has been emphatically expressed by the researchers.

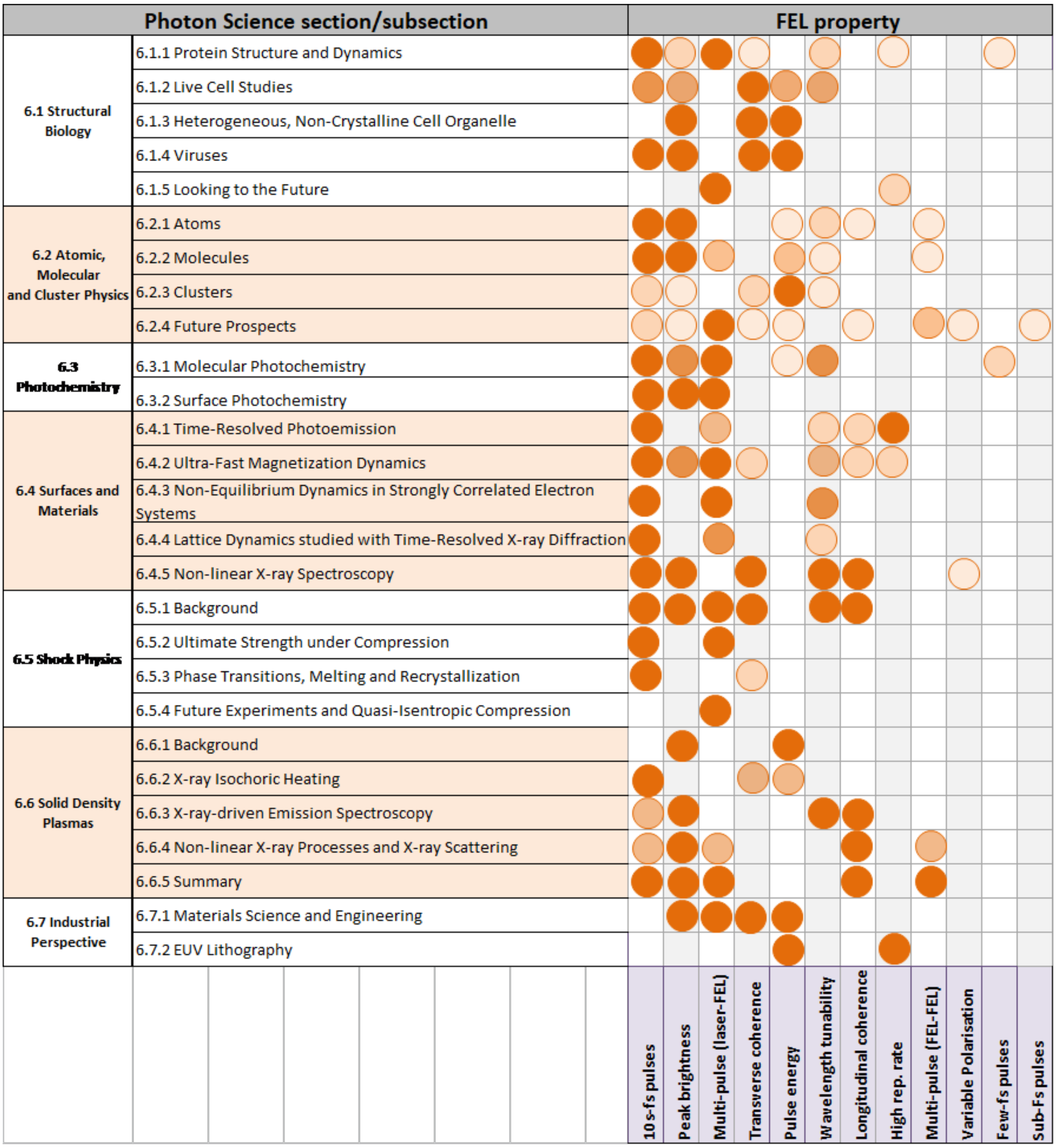


Figure 16: Main FEL properties required for the different Photon Science applications areas. Left side of the table reports the science section/subsection applications, down-right part the FEL performance with the photon pulse characteristics. On the right a line with coloured dots representing the strength of the link between the scientific applications and FEL photon pulse characteristics (darker dot: stronger link). Data from [27].

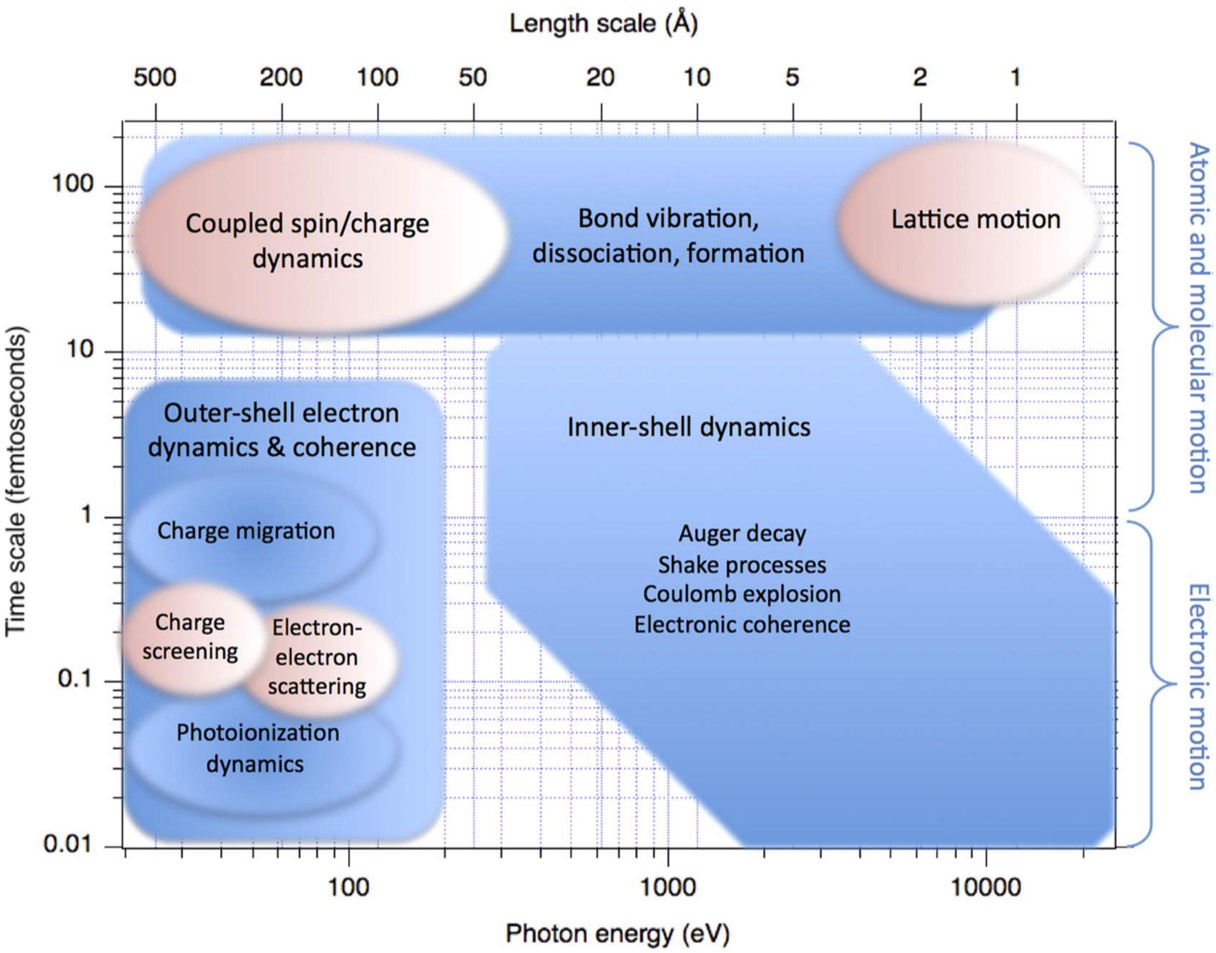


Figure 17: Characteristic time and energy scales of fundamental processes in atomic, molecular, electronic, spin and lattice systems. The characteristic length scales are indicated on the top bar. Data from [28].

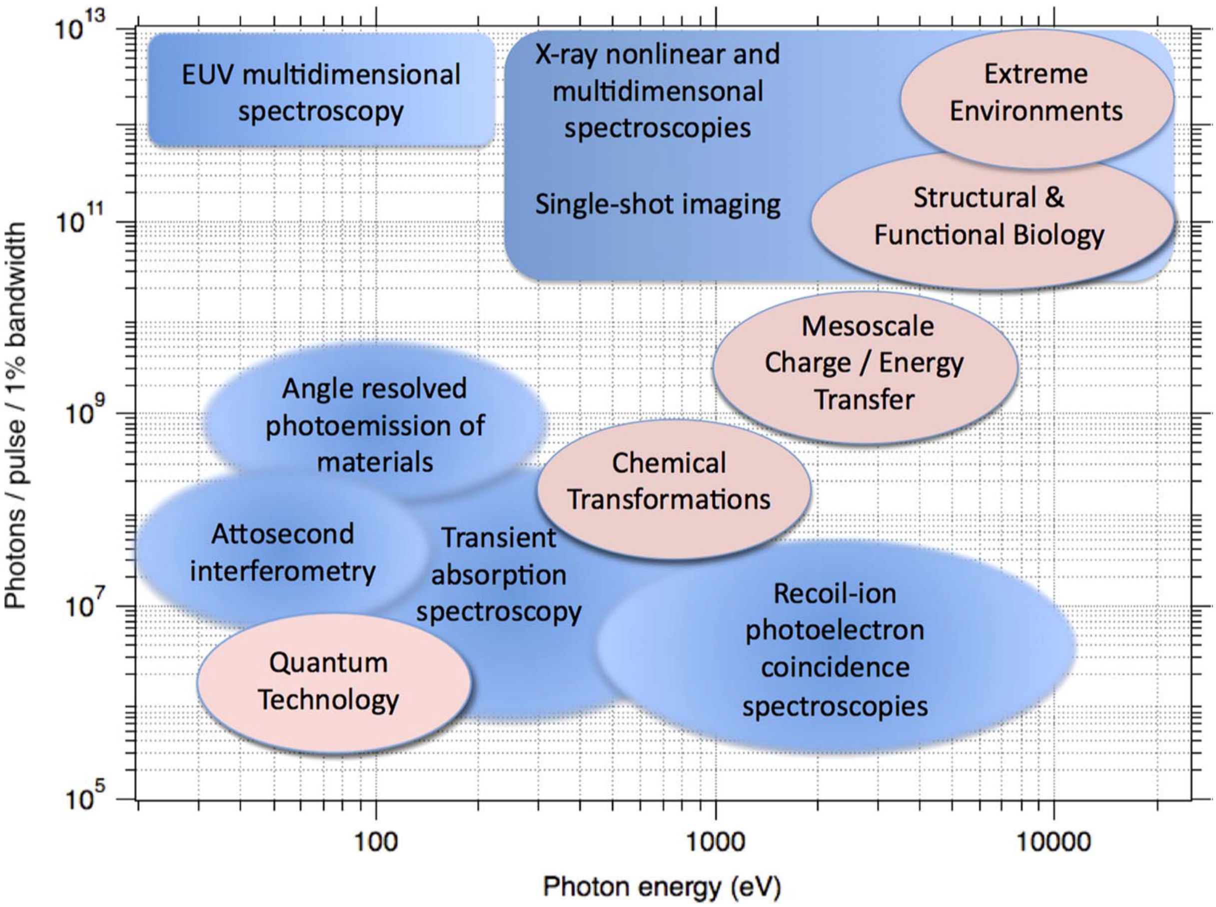


Figure 18: Number of photons per pulse into 1% bandwidth as required by different experimental ultrafast X-ray techniques (blue). The research areas relying on the techniques are shown in pink. The high-fluence regime enables nonlinear X-ray spectroscopies and single-shot imaging, potentially with atomic resolution. Data from [28].

3.3 Survey on user requirements

In conjunction with the CompactLight User Meeting held at CERN, a preliminary survey has been conducted through the use of an online questionnaire, sent to over 50 FEL experts within Europe. The purpose was to gather quantitative information about their requirements on the photon characteristics for current and future experiments.

The respondents have expressed interests in experiments such as (i) pump-probe diffraction, (ii) serial crystallography, (iii) time-resolved spectroscopy and (iv) time resolved scattering. In addition, each respondent has specified either one or two sets of desired parameter values for the future x-ray FEL. These parameter values are shown as histograms in figure 19.

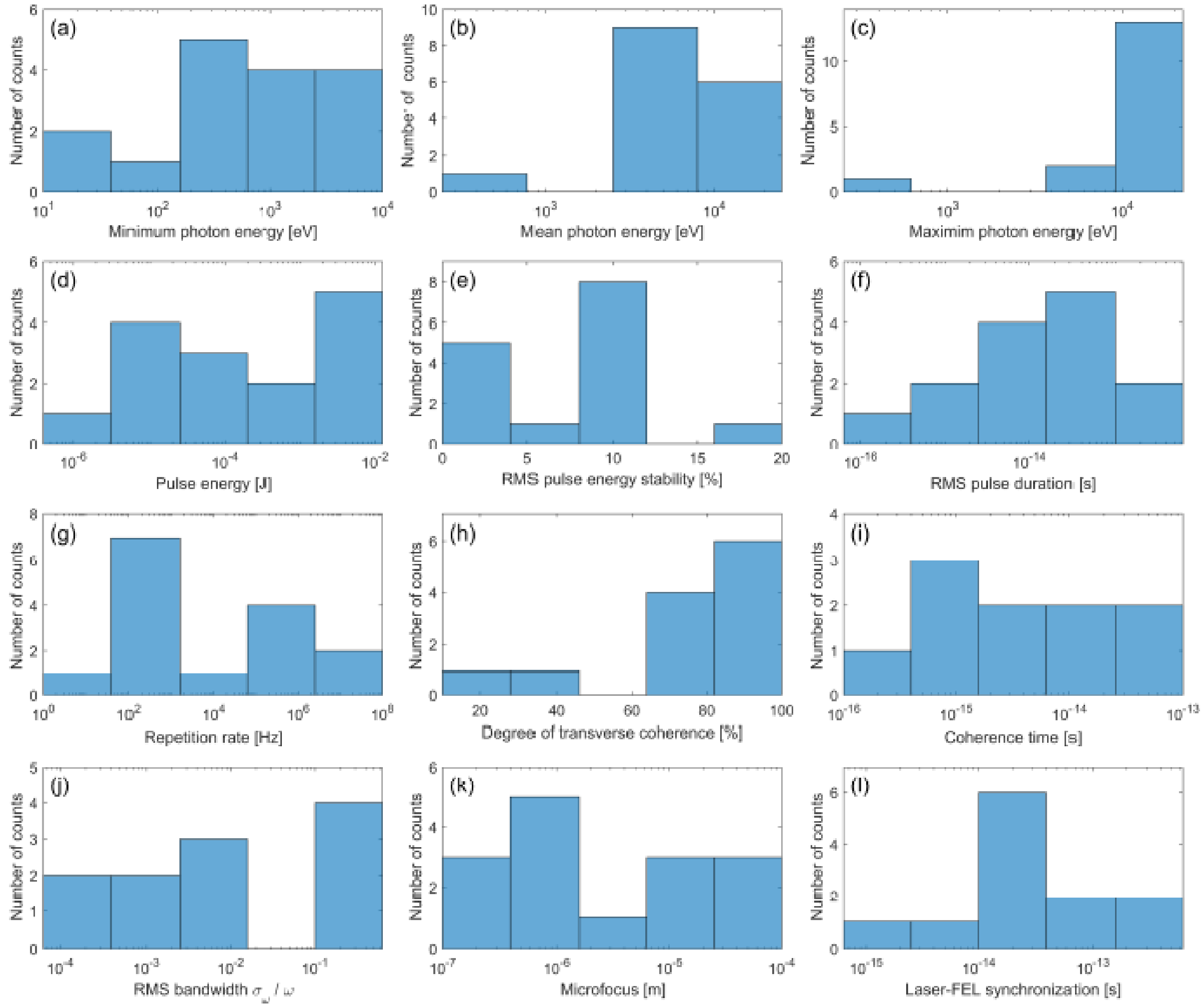


Figure 19: The results of the survey are summarized in histograms showing the users' requirements with respect to (a) minimum photon energy, (b) mean photon energy, (c) maximum photon energy, (d) pulse energy, (e) pulse energy stability, (f) pulse duration, (g) repetition rate, (h) transverse coherence, (i) longitudinal coherence, (j) bandwidth, (k) focused spot size and (l) synchronization between the FEL and the external laser.

With regard to the tunability, there is a clear demand for photon energies as low as 0.2 keV

[Fig. 3(a)] and as high as 20 keV [Fig. 3(c)]. The mean photon energy of the desired tunable range is about 4 keV [Fig. 3(b)]. The preferable pulse energy is in the range of 3-100 μJ [Fig. 3(d)]. Furthermore, the demand on the stability of the pulse energy is stringent and most respondents want the RMS fluctuation in pulse energy to stay below 12% [Fig. 3(e)]. A majority of the responding experts prefers a pulse duration of 10-100 fs [Fig. 3(f)], a repetition rate higher than 100 Hz [Fig. 3(g)], a degree of transverse coherence higher than 70% [Fig. 3(h)], a coherence time of 1-100 fs [Fig. 3(i)], a bandwidth of 0.1-1% [Fig. 3(j)] and a micro-focus of 0.1-100 μm [Fig. 3(k)]. For pump-probe experiments, most respondents want the synchronization between the FEL and the external laser to be in the order of 10 fs [Fig. 3(l)].

The questionnaire also has also asked the potential users to comment on any FEL feature that would benefit their future experiments. The answers are summarized as follows:

- variable polarization (linear and elliptical);
- pulse energy above 3 mJ;
- shorter pulse duration;
- higher stability in pulse energy and pulse duration;
- repetition rate of 1-10 kHz;
- laser-FEL synchronization better than 50 fs;
- FEL-pump FEL-probe capabilities with a large photon energy difference;
- small focused spot size;
- tunability extended to higher photon energies;
- better reliability of two-colour pulse generation.

Following these indications, but aware of the fact that one ideal X-ray source that can meet the current and future needs of all users does not exist, the XLS collaboration has distilled all the user input into a coherent specification that is fully aligned with the project's prime strategic objective, namely to generate a compact and affordable FEL facility design.

The main specification of the CompactLight design are summarized in table 3.

The facility output will cover the range between 250 eV and 16.0 keV with all photon energies within this range being accessible from at least one of the FEL beamlines. The 2.0 keV "boundary" between the soft-x-ray FEL and the hard-x-ray FEL will not be rigid, but will be determined considering electron beam energies, undulator performance, and X-ray optics capabilities.

To maximize the efficient operation of the facility, the tuning across photon energies will be achieved by undulator scanning rather than energy scanning. The FELs will be operated at a few discrete electron beam energies to achieve the full wavelength tuning ranges. Currently, a facility layout permitting to have a simultaneous operation of both the soft and hard X-ray FELs is under investigation.

Parameter	Unit	Soft X-ray FEL	Hard X-ray FEL
Photon Energy	keV	0.25-2.0	2.0-16.0
Wavelength	nm	5.0-0.6	0.6-0.08
Repetition Rate	Hz	100-1000	100
Pulse duration	fs	0.1-50	
Pulse energy	mJ	< 0.3	
Polarization	%	variable, selectable	
Two-pulse delay	fs	$\pm$100	
Two-colour separation	%	20	10
Synchronization	fs	< 10	

Table 3: Main parameters of the CompactLight FEL.

The XLS design is targeted at a repetition rate of 1000 Hz for the soft X-ray FEL and 100 Hz for the hard X-ray FEL, recognizing that a repetition rate of 1000 Hz would be a unique and desirable feature of the CompactLight design. It is a very challenging target for many systems, that the partners believe to be able to reach with a progressive approach.

Two pulses and two wavelengths are essential for many experiments and for this reason it is planned to develop a design that provides the two pulses and two wavelengths capabilities. In term of synchronization between different photon sources, for time-resolved pump-probe experiments, the intention is to provide a design that can synchronize the FEL with a conventional laser to better than 10 fs.

In terms of peak brilliance, the target performance of CompactLight is expected to be comparable to the state-of-the-art X-ray FEL facilities currently in operation, see figure 20.

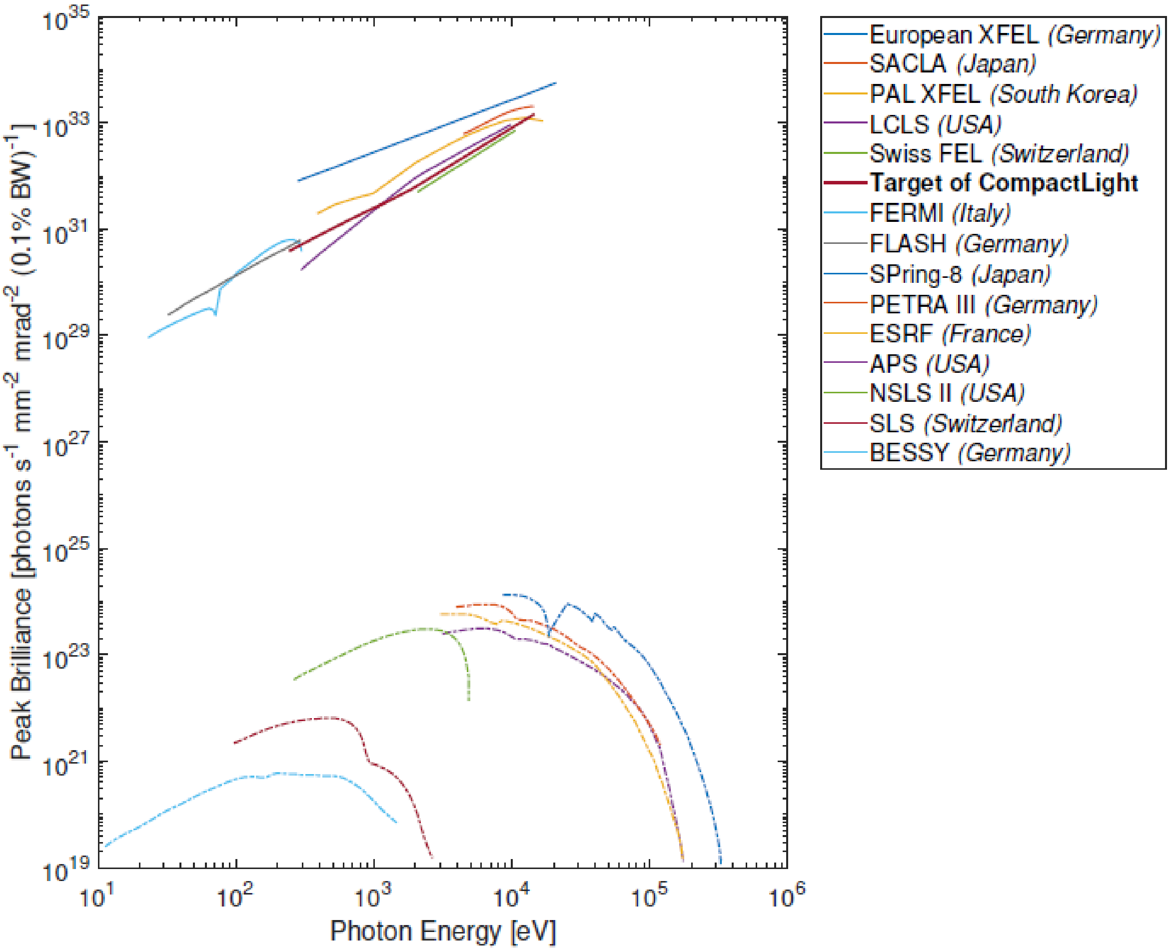


Figure 20: Peak brilliance as a function of photon energy for a selected set of x-ray sources. Free-electron laser facilities are shown in solid lines, and synchrotron facilities are shown in dashed lines [29].

3.4 Outlook

To consolidate and integrate the received information and to promote the use of the new technologies, further initiatives of user communication will be undertaken in the coming months, based on the actual, more advanced state of the project. Suitable activities have been discussed and defined during a recent face-to-face brainstorming meeting of the WP7 partners at ARCNL (third party of VU) in Amsterdam. The current section will be updated accordingly with supplementary results in the final deliverable D7.2.

4 Market Analysis

The following sections 4-7 are dedicated to the market, cost, SWOT, and risk analyses for the CompactLight project, which has the goal to deliver a novel and cost-effective X-ray FEL. The main objective of the presented analyses is to identify the attractiveness and the dynamics of academic, research, and industrial markets with a special focus on electron accelerators leading to novel X-ray FELs.

The analysis, which will be integrated to a full five pillar analysis (market, cost, SWOT, risk, technology) in D7.2, involves determining the unique characteristics of a very particular market and analyzing this information will help the collaboration as well as potential users of the technologies to make future decisions for business plans, taking into account the risks coming from certain choices to be adopted and to arrive at the most innovative, compact and cost-efficient solution for a new FEL. As such, it will collect and aggregate market data and information related to aspects pertaining to novel FELs and the intended products and applications driving development and exploitation. The analysis will be supported by already collected (see 3 and new data on the users' needs, the market size and its trends, the key drivers and the regulations, incentives and legal aspects. Additionally, it will assess the roles, expectations and benefits for different relevant stakeholders to understand how to leverage and engage them.

In the current chapter, section 4, the first results of the market analysis are presented.

4.1 Introduction

A market analysis is defined as the study of a project that presents information about the commercial market in which the project operates, the purchase and supply needs of users in this market, and informative elements of the competitors (note that 'users' are not necessarily scientific users, but can be users of the project results in a larger sense). It is based on market research and intended, with the proper strategy, to attract investors. A structural analysis will show, why a new and innovative product is a strong addition to a given market.

This section has the objective to provide critical information to the CompactLight collaboration partners that will enable them to refine the development of a product design with the best exploitation strategy for each selected application and geographical context. In addition, a proper methodology is presented within this framework with the aim of identifying the sectors, locations and the financial range with potential to enter the market as well as the associated current and future users. The market analysis will analyse and monitor critical aspects, opportunities, influencing factors and relevant actors, considering the following factors in relation to FELs:

- Market size
- Market trends
- Key markets and technological drivers
- Target countries analysis (France, Italy, UK, etc.)
- Innovation and transfer technology
- Applications and services

The analysis of the users' needs and research trends in 3 will support the market analysis, since it is crucial to understand the key actors' needs, desires and potential barriers to a specific implementation. This will facilitate to undertake proactive steps ensuring that the solutions offered by the project will match the user expectations, that possible synergies are being created, and that the project results will be used. The following areas will be taken into account in this section:

- Users interests
- Relevance to FEL
- Needs and challenges
- Benefits

The FEL market size and its trends are the starting point for understanding and analyzing the market and its business potential, with respect to the potential users interested in a novel FEL facility or in the upgrade of an existing one, complementary use opportunities, and specific scientific or non-scientific domains the users may be coming from. In this section the following questions are answered:

- How large are the potential markets for a FEL, future FEL upgrades, and complementary applications of the technology or single key components?
- Where do these potential markets stand geographically?
- What are the main forces and trends driving customers to purchase FEL products and services?
- Who are the potential buyers/sellers?
- What forces are preventing a FEL or other possible applications from developing its full potential?

This analysis is performed both globally and disaggregated by specific European target regions mainly in the Iberian, Baltic and South-East European areas, where no accelerator-based light sources or FELs currently exist [30].

4.2 CompactLight Complexity

It is important to stress the complexity of the CompactLight project [31], as it includes many novel technologies, hardware and software components, models, algorithms, standards, and potential IPRs. This complexity makes it difficult to identify the exploitable results from the beginning. The first key issue to be addressed is therefore to identify the individual potentially exploitable results in the workpackages (WPs) and the likelihood that they will be achieved by analysing the specific WP objectives and achievements.

These exploitable results can then be classified in three basic categories according to their type: 1-new knowledge, 2-software or hardware products and 3-services or methodologies. Each of these three types of product or service implies a different strategy towards exploitation.

For example, i) new knowledge should be disseminated between partners and the wider community, enabling them to contribute to further research or to innovations, while ii) in the case of software or hardware products, patentability should be examined and potentially a plan for commercial exploitation, for instance through the involvement of industrial partners or the creation of spin-offs, could be developed.

4.3 Market Analysis Methodologies

Having identified the type of exploitable results, different exploitation strategies can be adopted, namely those that

- make use of the results for scientific purposes or the general advancement of knowledge, for instance by utilising the results in scientific publications, educational materials, research roadmaps, etc. The dissemination of research results supports the advancement of knowledge very effectively. In this case, industry derives no competitive advantages from the information, because published results are automatically public domain and therefore accessible to everybody and all competitors in equal measure. This holds except for the industrial project partners, who are benefiting from earlier access to and deeper understanding of the achieved results as well as eventually own new know-how developed in the course of the project activities.
- make use of results for general industry and societal purposes. This means making use of results in standard guides, policy recommendations, etc.
- make use of results for commercial purposes. This is a key priority for European projects under H2020 and means that research results such as prototypes, software products, services, or methodologies are commercially exploited, for instance through patenting and licensing to third parties (technology transfer model) or through the creation of a new company (spin-off model).

4.4 Market Analysis Strategy

Hence, the first step in the strategy definition towards the exploitation task is to identify the expected exploitable results and decide for each of them the best exploitation strategy. The 3x3 matrix in figure 21 is mapping this objective.
Apart from identifying exploitable results, the exploitation interest of potential users and stakeholders needs also to be considered when developing an exploitation strategy. According to the EU recommendations for H2020 projects [32], the main target audiences can be categorized in four categories:

- Research communities, mainly interested in access to new knowledge and research opportunities through publications, data, research roadmaps that help to advance science.
- Companies and innovators, mainly interested in new know-how, technologies, prototypes, software products, standards that enable the creation of new business opportunities.
- EU policymakers, mainly interested in policy recommendations and reports that support decision-making.
- Society, interested in educational materials, new knowledge and skills, and all other types of beneficial impacts that may increase the quality of life.

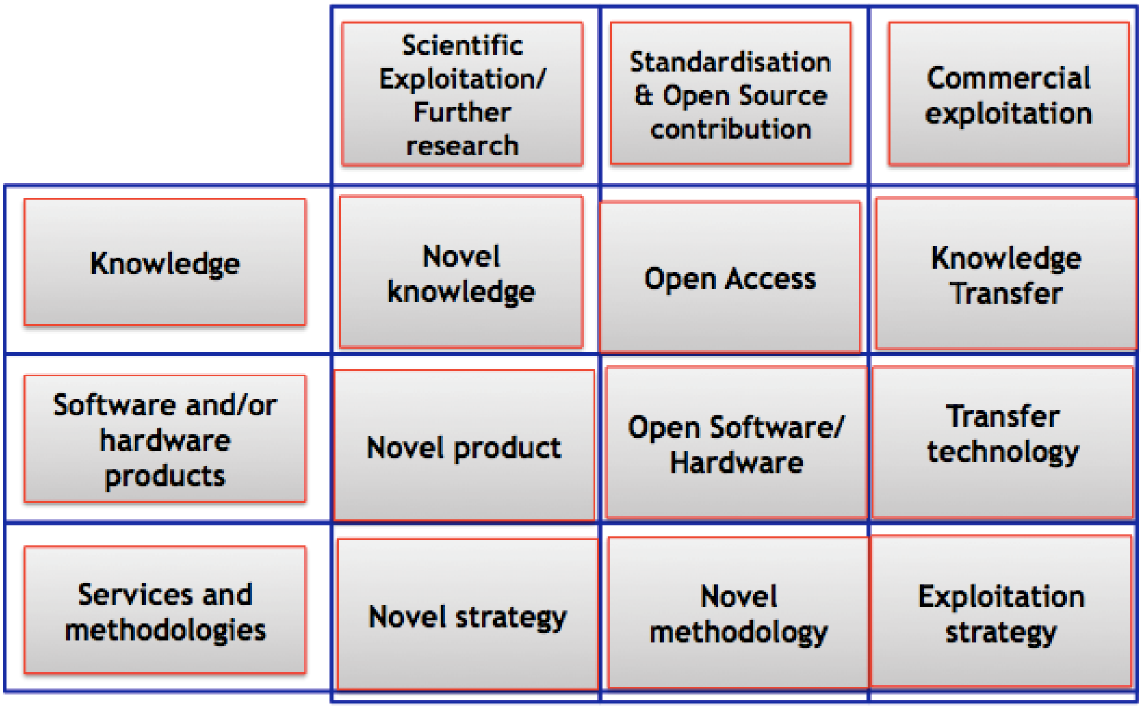


Figure 21: 3x3 matrix table presenting the strategy components towards the exploitation procedure [32].

4.5 Exploitation Plan

The exploitation plan will contain five important elements:

- The identification of the scientific and technical knowledge, products and services expected as results of the project.
- An in-depth analysis of the European and global markets, identifying relevant target markets and assessing the competitive environment surrounding the project.
- A proposition of alternative business models for exploitation, covering relevant aspects of value proposition, customers, and revenue models.
- Definition of the dissemination activities required for optimal exploitation.
- The assessment of the expected societal impacts of the knowledge and technology, such as standardization or regulatory aspects, as well as strategies for an appropriated management of the knowledge generated and the protection of the Intellectual Properties created by the project.

4.6 Exploitable Results

In order to identify the exploitable results, the appropriate exploitation approach for each outcome and the relevant stakeholders, input will be obtained by analysing the deliverables of the technical workpackages. Since the deliverables might not give all the important information regarding the exploitation potential, the following additional activities are planned:

- To organise internal workshops with the WP leaders or representatives from WPs to capture the exploitable results and their potential, e.g. through remote semi-structured face-to-face focus group interviews.
- To measure the perceptions of internal stakeholders and potential future users through surveys. A survey will in particular capture the interest of the single project partners in exploiting the results from their project activities with regard to their own organization, their vision, as well as their actual and their future product / service / process portfolio.

The main topics to be addressed during the internal workshops and the survey will be

- the type of result and its innovation content (product, process, software, service, etc.)
- innovation of the product, e.g. whether it will be beyond the state of the art;
- the resulting efficiency gain for the customers, collaboration partners, public, etc;
- the Technological Readiness Level (TRL) of the result and the progression up to TRL9[3];
- the main technical challenges for reaching the project result;
- the estimated time to market (Mth/yr) for the technology / a possible product;
- the intention of the project partners to protect the project result before disclosing it.

It is also important to define the ultimate outcome of the internal workshops and to delineate the most promising results from the exploitation point of view.

4.7 Outlook

The results of the complete Market Analysis for CompactLight FELs, complementary technology use and major components, including the exploitation strategy beyond the project duration will be presented in the deliverable D7.2 in the end of the project.

5 Cost Analyses

5.1 Introduction

Cost and performance models of the technical systems of research infrastructure projects are usually based on simulations and prototypes. These and existing models of other light sources and middle to large size accelerator facilities [34–37] are taken into account as part of the CompactLight project cost analysis. The scope of this analysis covers the technical systems (injector, linac and undulator) and associated beam dynamics. Also considered are the costs and estimated budgets required for the construction and operation of this kind of facility, including the civil engineering work and the conventional services. A comparison of costs with an existing facility and, if possible in terms of time and effort, with FEL projects will be made, considering already committed investments. An excellent example of a cost analysis for a large accelerator-based light source to gain experience and know-how for the CompactLight project is that of the European XFEL [38].

[3]**TRL 9 (TRL Scale in Horizon 2020 and ERC)** - Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space). [33]

5.2 CompactLight Cost Analyses

For the CompactLight cost analysis a bottom-up approach has been chosen, starting at the lowest level with the identification of the component costs and of their multiplicity. The cost in the estimate is expressed in Euro and considers the value of manufactured components, which already includes the cost of personnel by the supplier. The uncertainty of the cost estimate has been evaluated by taking into account on the one hand the technical maturity of the adopted solutions and on the other hand the uncertainty in the industrial procurement process (Ref. [39]). Three levels of uncertainty have been associated to the technical risk, by assuming 10 % uncertainty when the technology is already available, 20 % uncertainty is considered when an extrapolation is needed from a known technology and finally 30 % uncertainty is used when a technology requires additional R&D. The uncertainty in the industrial procurement process has been extracted from the model following the study of procurements during the LHC realization. The standard deviation of the cost distribution has been considered as $\sigma = 0.5/n$ with n the number of valid offers received. The total uncertainty is then calculated by adding quadratically the two standard deviation values for the two classes of uncertainty.

Since the CompactLight project aims at providing a site-independent facility design, it has been chosen that all costs associated to civil engineering realizations and the general infrastructure refer to manpower and civil engineering cost in the UK, as a reference; however they should be translated to the site specific cost of civil engineering construction and infrastructure when a particular country is then considered for the facility. The cost of land acquisition was not included into this study.

5.3 The CompactLight PBS

The data have been organized in the same costing tool that was already developed for the cost estimate of the CLIC project. The tool is an interface between the user and a large database where the information is stored and secured. The CERN Advanced Information Systems team (AIS) has provided a dedicated interface specifically prepared for the CompactLight project.

The costing tool includes features for fixed and variable costs, currency conversion, escalation and uncertainty, as well as full traceability of input data and production of tabulated reports which can be exported for further processing.

Since the CompactLight study considers a baseline facility with the possibility to upgrade it to two higher performance levels, with increasing complexity, the tool allows to separately estimate the cost of the baseline and of the upgrades and also to include the chosen optional upgrade in the overall cost of the facility.

The cost information has been organized in a project breakdown structure (PBS), which considers four levels providing increasing detail starting from the Machine Sector down to System, sub-System and Component. Each Machine Sector has been associated to a work package and the work package leader was asked to provide the cost information for the items under his responsibility. An iterative process has been followed, with increasing completeness and accuracy of the estimate.

In figure 22 the PBS structure is shown for the CompactLight baseline.
A limited use of learning curves has been done for some components, like klystrons, as an example, for which a prototype cost estimate exists and an extrapolation is required for providing a cost value for the relatively small series production needed by the CompactLight design. More in general the costing is based on the experience gained with previous installations by the different experts contributing to the work package. In some cases it was decided to produce the estimate at the system level, without going into the details of the components, when a cost scaling has been possible by applying scaling laws to similar items.

R&D activity and the development of prototypes have not been explicitly included in the cost estimate, however they are implicitly considered, partially, in the margin of uncertainty of the estimate itself.

5.4 Case Study: SwissFEL

The SwissFEL has characteristics comparable to those envisaged for the CompactLight FEL and is thus the perfect example for cost comparisons. For this reason it has been selected for an in-depth case study for which the first results will be presented here.

The cost comparison of the SwissFEL with other similar facilities in the world, shown in figure 23, provides a good basis for establishing a cost estimation for the CompactLight case.

Figure 24 shows the results of a cost optimisation exercise for the linac of the SwissFEL. The SwissFEL team has investigated these costs, in terms of investments and power consumption over 10 years, as a function of the voltage gradient (MV/m) for the S-band with klystron powers of 45 MW (S45, red lines) and 80 MW (S80, green lines) and for the C-band with a klystron power of 50 MW (C50, blue lines).

The figure indicates minima of the total linac costs at specific gradients that depend on the particular band and the used klystron power (S45: 18.5 MV/m, S80: 22.0 MV/m, C50: 27.5 MV/m). In this scenario, the C-band option appears to be the optimum solution with regard to the total costs, due to reduced real estate needs and lower power consumption.

A similar investigation, presented in Fig. 25, has been conducted for the SwissFEL, SACLA and LCLS power consumption (MW) as a function of the RF plant's repetition rate (Hz).

The plots in Fig. 25 have been extracted from the equation below, where P_{HF} (MW) is the radio frequency systems power consumption, V (MV/m) the electric accelerating field, E (GeV) the beam energy and R'(MΩ/m) the effective resistance with correction for pulse compression. The values of these parameters for the three facilities are shown in table 4.

$$P_{HF} = \frac{V \cdot E}{R'}$$

For figure 25, a well-established methodology was applied, trying to combine small beam emittance with short period undulators for the beam energy with a compromise on the power

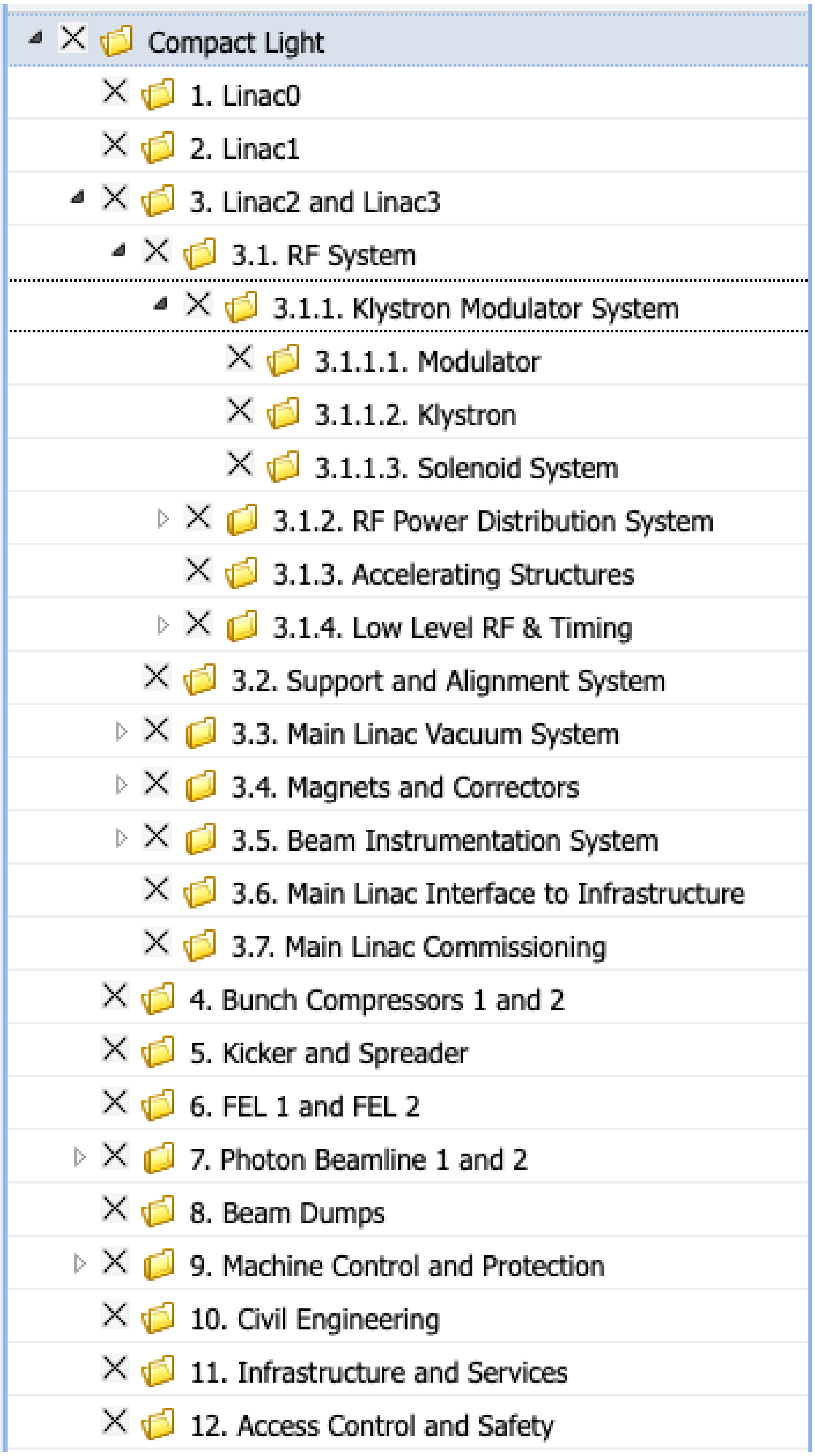
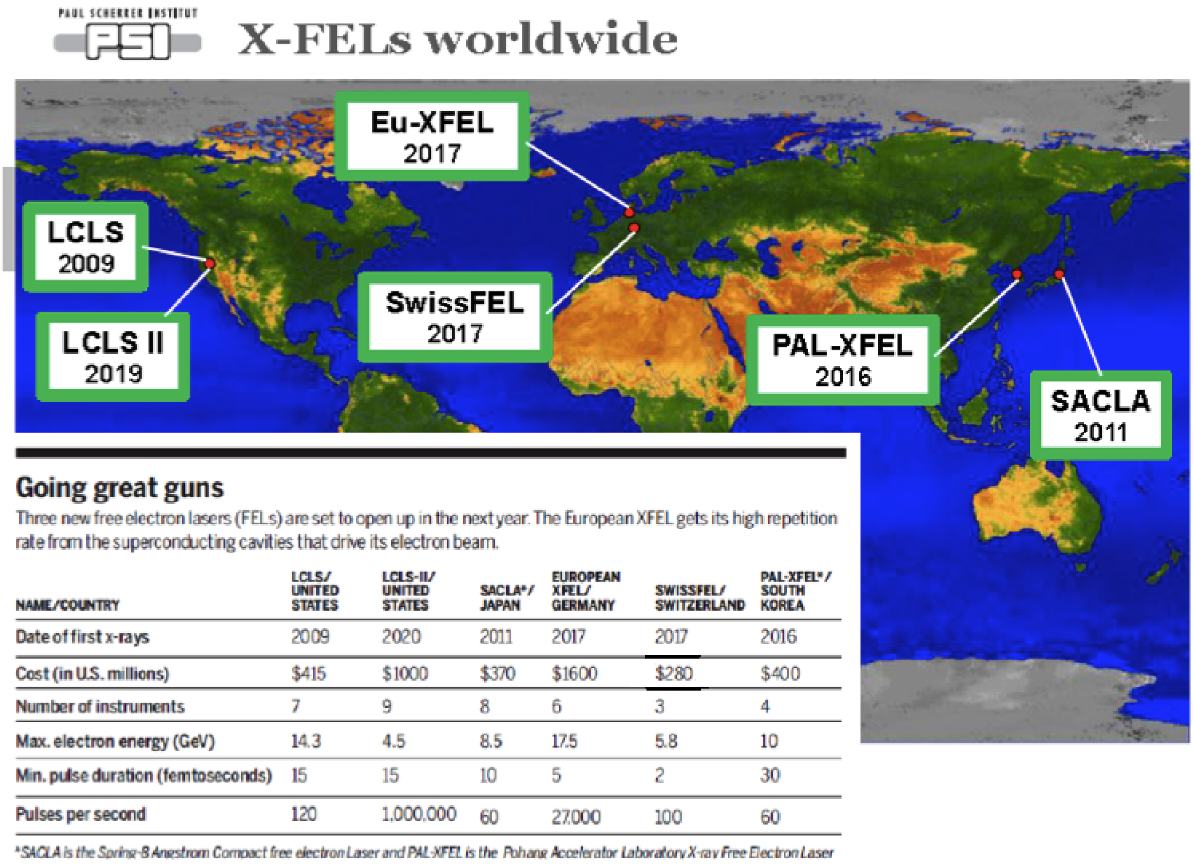


Figure 22: PBS structure for the baseline layout of the CompactLight facility. The multi-level organization is highlighted.



Going great guns

Three new free electron lasers (FELs) are set to open up in the next year. The European XFEL gets its high repetition rate from the superconducting cavities that drive its electron beam.

NAME/COUNTRY	LCLS/ UNITED STATES	LCLS-II/ UNITED STATES	SACLA*/ JAPAN	EUROPEAN XFEL/ GERMANY	SWISSFEL/ SWITZERLAND	PAL-XFEL*/ SOUTH KOREA
Date of first x-rays	2009	2020	2011	2017	2017	2016
Cost (in U.S. millions)	\$415	\$1000	\$370	\$1600	\$280	\$400
Number of instruments	7	9	8	6	3	4
Max. electron energy (GeV)	14.3	4.5	8.5	17.5	5.8	10
Min. pulse duration (femtoseconds)	15	15	10	5	2	30
Pulses per second	120	1,000,000	60	27,000	100	60

*SACLA is the Spring-8 Angstrom Compact free electron Laser and PAL-XFEL is the Pohang Accelerator Laboratory X-ray Free Electron Laser

Figure 23: Map of the worldwide operating XFEL facilities and table of their construction costs [40].

	V (MV/m)	E (GeV)	R'(MΩ/m)
SwissFEL	28	5.8	168
SACLA	35	8.0	125
LCLS	17	13.6	80

Table 4: Optimum values of the accelerating field V (MV/m), beam energy E (GeV) and effective resistance for the FEL facilities SwissFEL, SACLA and LCLS.

consumption and the facility length for the accelerating field, taking into account a C-band frequency structure geometry of the pulse compression for the effective resistance. Table 4 shows the optimum values for each of the three facilities.

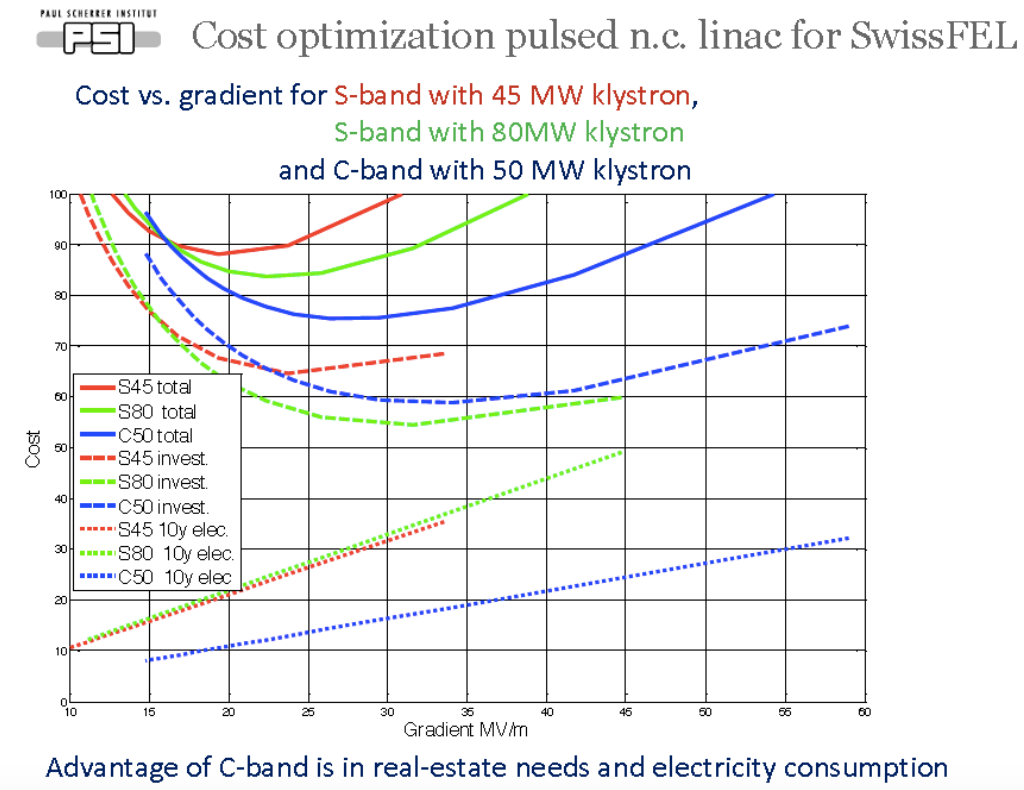


Figure 24: SwissFEL costs for the C-band and S-band options as a function of the voltage gradient; dashed lines refer to the investment costs, dotted lines to the power consumption over 10 years of operation, solid lines to the total costs. (MV/m) [40].

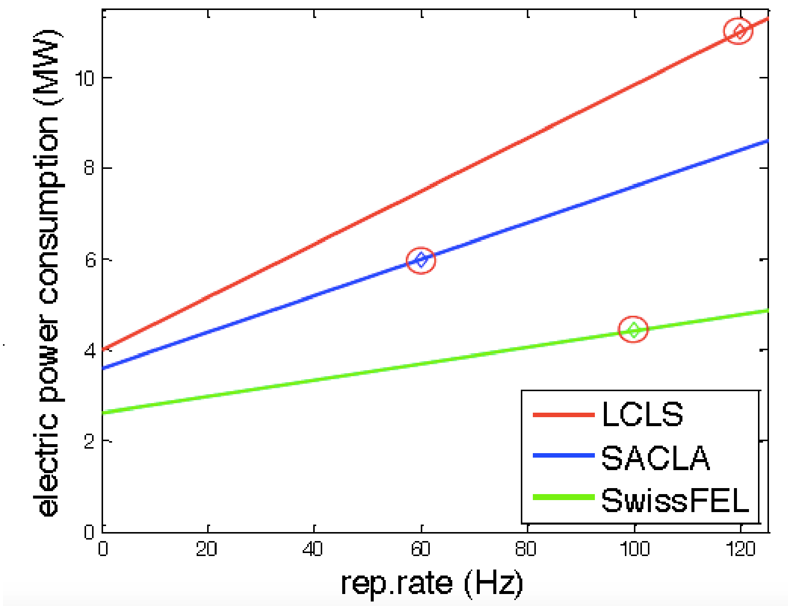


Figure 25: SwissFEL, SACLA and LCLS operation power consumption versus the RF plant's repetition rate (Hz); the points on each line correspond to the optimum operation values for each facility [40].

5.5 Outlook

Obviously, a serious cost analysis of the project needs to be based on the real layout of the CompactLight facility, including the details for the different subsystems. Since simulations for different options have been carried out for the various components until now, an agreement on a final layout could only be achieved recently among the partners and no cost estimates exist at the moment. However, as reported in 5.3 the Project Breakdown Structure for the cost analysis has been created and meanwhile also first costing data have been collected from the different WPs. A comprehensive cost analysis of the facility, based on a suitable level of detail for the various parts and sub-parts of the system in order to achieve a realistic picture, will be provided in the final deliverable D7.2. These costs will then be compared to the costs of other, comparable facilities (insofar as these are available). In particular, the case study of the SwissFEL will be carried on during the last project year and a comparison between the costs of SwissFEL and CompactLight FEL will be prepared. The complete study will be presented in D7.2. Additionally, the document will also contain cost estimates of components and subsystems that might be used in other types of facilities both, in research or other sectors.

6 SWOT Analysis - Strengths, Weaknesses, Opportunities, and Threats

6.1 Introduction

In order to validate the business opportunity of the final project design, a SWOT analysis of CompactLight will be performed. In this type of analysis the Strengths, Weaknesses, Opportunities, and Threats of a project, business, technology or product are identified [41][12]. This includes also a study of potential competitors with an evaluation of their strengths and weaknesses and yields finally a statement on the competitive advantage of the investigated project, business, technology or product over the competing ones.

6.2 Market and Industry Research: The Seven Domain Model

The idea is to use the seven-domain framework model developed by Mullins [42] regarding the market and industry research. This model offers a toolkit for assessing and shaping market opportunities and provides an answer to the question, whether a product is attractive for a market or industry. Information about the current market will be obtained by researching trends and analyzing the competition.

The model brings some crucial distinctions and observations to light that should not be overlooked:

- Markets and industries are not the same things.
- Both macro- and micro-level considerations are necessary: markets and industries must be examined at both levels.

- What is the estimated size of the market for the product/service?
- What is the projected market share?
- Is the current market attractive for the product/service?
- Are there any predictions for future trends?
- Which are the existing business models?

The proper answers to the above questions lead to the best path for guiding the project to the correct policy in terms of the market and industry research analysis.

6.3 Competition Analysis

An in-depth investigation and analysis of the competition is one of the most important components of a comprehensive market analysis. A competitive analysis allows the competitor's strengths and weaknesses in the marketplace to be assessed and to develop effective strategies to improve the competitive advantage. For that reason, a continuous contact and update about competition, either existing or emerging alternative solutions is required.

6.4 Business Model Generation

The Business Model Canvas is a strategic management template for developing new or documenting existing business models. It is a visual chart with elements describing a firm's or productss value proposition, infrastructure, customers, and revenue model. It is a formal way to design the business models for each of the retained results, analyze alternative routes to market, analyze the impact of project results on traditional business models and the potential of new business models in this area [43, 44].

In figure 26 the business model components, which will be addressed during the project work, are summarized.

6.5 Preliminary CompactLight SWOT Analysis

These are, in brief, the preliminary outcomes of the SWOT analysis for CompactLight:

Strengths

- New design with improved specifications compared to existing facilities.
- Active and broad collaboration with experienced teams in the project.
- Experienced industrial collaboration partners from relevant sectors.
- Academic partners with project-relevant expertise in key fields of science, engineering, finance & economy.
- Less expensive final product as compared to existing facilities with a comparable performance.

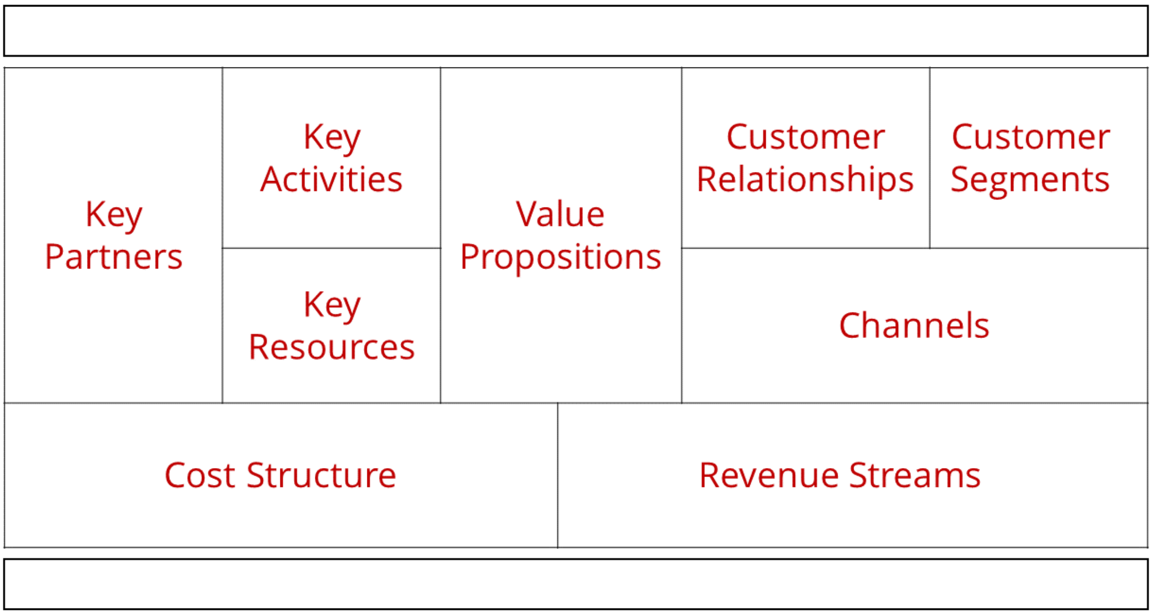


Figure 26: Summary of the Business Model Components.

Weaknesses

- Final technological options for various parts, i.e. the layout for the X-band or the type of undulators not yet defined.
- Effort to cover more areas of X-ray production as foreseen in the original project plan.

Opportunities

- Large areas without light sources in Europe and elsewhere for implementation of the final product.
- Cooperation development with institutions and countries to commercialize the final product.
- Creation of strong relationships with major European networks of light sources and FELs (i.e. LEAPS [4], FoE [5].

Threats

- Further XFEL projects already currently under development, but not yet in all areas in Europe.
- Different technology projects providing S-, C-, and/or X- band X-rays.

These preliminary results of the SWOT analysis are presented in Table 5. As a first approach, the CompactLight collaboration should keep focused on a simple basic design option satisfying the requirements set in the project proposal. If possible within the limits of the project, upgrading options of the basic design can also be proposed.

[4] League of European Accelerator-based Photon Sources, https://leaps-initiative.eu/
[5] FELs of Europe, https://www.fels-of-europe.eu/)

	Opportunities (external, positive)	**Threats** (external, negative)
Strengths (internal, positive)	**Strength-Opportunity Strategies** Novel & compact design, engineering, finance & industrial partnership, novel components (e-gun, undulators ...)	**Strength-Threat Strategies** Other FELs under development
Weaknesses (internal, negative)	**Weakness-Opportunity Strategies** Improved specifications compared to competing FELs	**Weakness-Threat Strategies** Too many technological options in one facility to satisfy the large variety of user demands

Table 5: The SWOT components combination is presented, providing the correct strategy directions.

6.6 Outlook

A complete and refined SWOT Analysis of the CompactLight FEL source, which is currently under way at AUEB, will be presented in the end of the project in D7.2.

7 Risk Analysis

7.1 Introduction

Risks are defined as the probability of occurrence of a harmful event times the impact of this event [45].

The integrated risk management process supports a successful implementation of an infrastructure project during the design phase. The risk analysis should therefore be managed properly [46] in order to avoid negative impacts on the project economics, such as cost overruns and time delays.

7.2 Risk Management for CompactLight

For the potential future application of the CompactLight design, several risk management standards from the literature (i.e. PMBOK, CAN/CSA-Q850-97, RISMAN, FERMA and IRM, IEC 62198:2013, PRAM, BS6079-3:2000 and ATOM) have been studied based on the following criteria, which are crucial for a proper risk management process:

- Risk identification
- Risk assessment
- Analysis and treatment
- Risk response
- Risk control
- Monitor and Review

Through this study of the risk management process, the need to improve the factors that influence the quality of performance of projects using the CompactLight design became evident. In this report, a preliminary risk analysis is presented.

- **Identification:** is focused on listing all the machine components, called nodes, related with failures and operation modes.
- **Combination:** is listing all potential failures for every node in any mode of the XFEL operation.
- **Analysis:** is conducted in 2 steps:
  1. **First:** For each potential failure a YES/NO decision is made to retain credible failures only.
  2. **Second:** 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.

On this basis, 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.

7.3 Preliminary Results for CompactLight

Table /reffailure-risks presents all the cases for CompactLight analytically. Failures of gravity 1 do not create any risk, neither to the machine nor to other sources. For the failures of gravity 2 and 3, the associated risks are described and recommendations are formulated, following the practice used for the cryogenic system of the Large Hadron Collider at CERN [47, 48].

	Gun	Inj	Linac	BuCo	Undu	Kly	Power	BCS	Time	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

Table 6: Descriptive analysis of the causes and consequences of each credible failure with gravity numbers of 1 to 3.

The results of the Compact Light risk analysis are described in table 6. In the table, the identification nodes describing the possible systems and categories at risk of failure are Gun (rf-Gun), Inj (Injector), Linac, BuCo (Bunch Compressor), Undu (Undulators), Kly (Klystrons, Power (Power System), BCS (Beam Control System), Time (Project Time Schedule), and Cost (Project Costs). The failure nodes for an infrastructure project are Construction, Commissioning, Operation, Technical Failure, Power off, Time Delay and Budget Limit.

7.4 Outlook

The risk analysis will be further developed in close collaboration with AUEB during the last year of the project and presented in detail in deliverable D7.2.

8 Open Data

8.1 Introduction

In general terms, our research data should be 'FAIR', that is Findable, Accessible, Interoperable and Re-usable. These principles precede implementation choices and do not necessarily suggest any specific technology, standard, or implementation-solution.

The purpose of the data production, collection and processing is to gather all the technical and scientific information produced by the XLS collaboration, which is defined as "open" by the partners. The partners are collecting technical / scientific as well as administrative data in order to deliver a coherent and fully documented Conceptional Design Report (CDR) at the end of the project. All these data could be used subsequently by other researchers and hence promote the knowledge dissemination for the benefit of the scientific society.
There will be various types and formats of project data to be collected. The collected data should be stored to one of the two categories: Scientific Data and Administrative Data.

8.2 CompactLight Data Storage: EDMS

CompactLight is utilizing CERN's own Engineering & Equipment Data Management Service (EDMS), which serves at CERN as the main Product Lifecycle Management (PLM) system and Enterprise Asset Management system. Much more details on how CERN is using this system, features and tutorials can be found under https://edms-service.web.cern.ch/.

EDMS enforces unique identifying numbers. The system allows for direct search of the respective EDMS numbers as well as any query containing author, keyword, creation date range. Additionally, documents in EDMS are attached to (multiple) hierarchical projects. Individual documents can hence be found also through simple navigation of the relevant projects and nodes.

The project data storage and archiving system EDMS has an in-build function of versioning, visually displaying all previous states of documents and allowing only the current one to be altered. For documents for which specifically multiple updated versions are planned, e.g. the Data Management Plan (DMP), version numbers are explicitely added in the documents themselves.

The project is documenting any information available and necessary in order to be able to recreate the entire design process. One example is simulation output data, which is complemented with simulation code documentation as well as input parameters and tools/functions used. Specifically, for the numerical simulations for which tailored computer codes are being used, CERN's GitLab environment with all its Git features and possibilities is employed. For all further standard data sets, e.g. engineering design and cost analysis data, EDMS allows for an exhaustive set of predefined information fields where useful meta data information can-/must be attributed to the respective documents directly.

The web based system allows for direct queries or browsing through hierarchical structures in order to find the desired data set or information. No specific software tools are necessary and access to the service is available from all over the world.

The CERN hosted EDMS system is free to use for CERN-related activities (XLS qualifies for this criterion through the role of CERN being a partner of the project) and the XLS data will be saved, archived and backed up according to CERN standard procedures along with all the rest of the CERN engineering data.

There is an extensive guide on how to use EDMS readily available at CERN under https://edms-service.web.cern.ch/edms-service/faq/EDMS/pages/tutorials.html.

8.3 CompactLight Data Policy

Most of the scientific and technical data will be openly available once finalized, such as technical specifications or simulation results. Snapshots of various developments and data sets will be published in international scientific journals or presented in international conferences and published in their proceedings.

Some of the sensitive Administrative Data cannot be available, i.e. detailed financial data concerning the budget of each participating institution. This restriction is also derived from the internal rules and regulations applied by each institution in those matters, as well as from current European law. In the CompactLight project, data can be open or kept confidential for exploitation according to the provisions of Grant Agreement and Consortium Agreement.

There will be no restrictions for access to open data. As for the sensitive data, access can be granted through the CERN implementation of e-groups. Potential users of the data can obtain access rights through acquiring a CERN lightweight computer account and being added to the relevant e-group. For the duration of the project, the access for externals will be granted by the project coordinator on an on-demand case.

Most of the scientific data and administrative data will be cast in the form of reports or publications, hence usable with any office productivity suite. Raw data of measurements (where applicable) or simulation output will be stored in plain text, ascii file format or similar, containing headers for data type identification. Hence special software will be necessary for performing post-project analysis. If requested, specifically developed computer codes can be provided for cross checking of results.

The scientific data produced by CompactLight will be accessible without licence immediately after publication. Some of the more sensitive administrative data (such as company offers, cost and schedule estimations, etc.) will be freely accessible at latest after the end of the project. Access to and the maintenance of the full data set will be ensured according to the data policy of CERN.

8.4 Outlook

For D7.2, the information on available 'Open Data' of CompactLight, access possibilities, and possible user support provided by the project beyond its duration will be integrated, if necessary.

References

[1] E. Elder et al., *Radiation from Electrons in a Synchrotron*, Physical Review **71** (1947) 829, DOI: 10.1103/PhysRev.71.829.5, URL: https://link.aps.org/doi/10.1103/PhysRev.71.829.5.

[2] K. Codling, *Atomic and Molecular Physics Using Synchrotron Radiation - the Early Years*, Jornal of Synchrotron Radiation **4** (1997) 316, DOI: 10.1107/S090904959701162X, URL: https://doi.org/10.1107/S090904959701162X.

[3] E. Lohrmann, P. Söding, *Von schnellen Teilchen und hellem Licht - 50 Jahre Deutsches Elektronen Synchrotron DESY*, 2nd, Wiley VCH Verlag, Weinheim, 2013, ISBN: 9783935702713.

[4] G. Margaritondo, *Synchrotron light: a success story over six decades*, Rivista del Nuovo Cimento **40** (2017) 411, DOI: 10.1393/ncr/i2017-10139-3, URL: https://www.sif.it/riviste/sif/ncr/econtents/2017/040/09/article/0.

[5] P. Emma et al., *First lasing and operation of an ångstrom-wavelength free-electron laser*, Nature Photonics **4** (2010) 641, ISSN: 17494885, DOI: 10.1038/nphoton.2010.176.

[6] B. W. Mcneil, N. R. Thompson, *X-ray free-electron lasers*, 2010, DOI: 10.1038/nphoton.2010.239.

[7] C. Pellegrini, *The history of X-ray free-electron lasers*, European Physical Journal H **37** (2012) 659, ISSN: 21026459, DOI: 10.1140/epjh/e2012-20064-5.

[8] LEAPS, *LEAPS Landscape Analysis*, tech. rep., League of European Accelerator-based Photon Sources, 2019, p. 1, URL: https://leaps-initiative.eu/about/leaps-documents/.

[9] E. Barrier et al., *The benefit of the European User Community from transnational access to national radiation facilities*, Journal of Synchrotron Radiation **21** (2014) 638, ISSN: 16005775, DOI: 10.1107/S1600577514007619.

[10] N. Martensson, M. Eriksson, *The saga of MAX IV, the first multi-bend achromat synchrotron light source*, 2018, DOI: 10.1016/j.nima.2018.03.018.

[11] M. Magnuson et al., *List of contributors*, 2006, URL: http://liu.diva-portal.org/smash/record.jsf?pid=diva2%3A358131&dswid=-4157.

[12] MAX-LAB, *MAX IV Detailed Design Report on the MAX IV Facility*, tech. rep., Lund: MAX-lab, 2010, URL: https://www.maxiv.lu.se/accelerators-beamlines/accelerators/accelerator-documentation/max-iv-ddr/.

[13] R. Dimper et al., *ESRF Upgrade Programme Phase II (2015-2022) - Technical Design Study*, tech. rep., Grenoble: European Synchrotron Radiation Facility, 2014, p. 194.

[14] Elettra Sincotrone Trieste, *Elettra 2.0 Preliminary CDR (Mk.1)*, tech. rep., Trieste: Elettra Sincrotrone Trieste, 2018, p. 178, URL: https://www.elettra.trieste.it/lightsources/elettra/elettra-2-0.html?showall.

[15] Elettra Sincrotrone Trieste,
Facts and Figures: Users at Elettra, in: Elettra Highlights 2010-2019,
URL: http://www.elettra.trieste.it/science/highlights.html.

[16] ESRF - European Synchrotron Radiation Facility, *ESRF Highlights (different years)*,
URL: http://www.elettra.trieste.it/science/highlights.html.

[17] ALBA-CELLS, *ALBA Activity Report 2017*,
URL: https://www.cells.es/en/media/corporate-publications/corporate-publications.

[18] MAX IV Laboratory, *Annual Report of the MAX IV Laboratory to the Swedish Research Council, years 2017 and 2018*, URL: https://www.maxiv.lu.se/science/reports/.

[19] CLIO, *CLIO Website*, URL: http://clio.lcp.u-psud.fr/.

[20] Elettra Sincrotrone Trieste,
Facts and Figures: Users at FERMI, in: Elettra Highlights, editions 2010-2019,
URL: http://www.elettra.trieste.it/science/highlights.html.

[21] H.-H. Feidenhans'l, *Welcome to the 2019 European XFEL Users Meeting - the 13th Users Meeting, presentation, 23/01/2019*, Hamburg, 2019.

[22] PSI - Paul Scherrer Institut, *SwissFEL's First Call for Proposals*, 2019,
URL: https://www.psi.ch/en/psd/scientific-highlights/swissfels-first-call-for-proposals.

[23] PSI - Paul Scherrer Institut, *Facts and Figures: Statistics for the year 2018*, 2019,
URL: https://www.psi.ch/en/about/facts-and-figures.

[24] CORDIS, *Cordis Project Database*, URL: https://cordis.europa.eu/search.

[25] ESUO, *European Synchrotron User Organisation: Towards even brighter European Photon Science*, URL: http://www.wayforlight.eu/en/users/esuo/.

[26] R. S. Romaniuk, *ARIES - Development of Accelerator Technology in Europe 2017-2020: Global and Local Consequences*,
International Journal of Electronics and Telecommunications **63** (2017) 109,
ISSN: 20818491, DOI: 10.1515/eletel-2017-0015.

[27] E. A. Seddon et al.,
Short-wavelength free-electron laser sources and science: A review, 2017,
DOI: 10.1088/1361-6633/aa7cca.

[28] L. Young et al., *Roadmap of ultrafast x-ray atomic and molecular physics*,
Journal of Physics B: Atomic, Molecular and Optical Physics **51** (2018) 032003,
ISSN: 0953-4075, DOI: 10.1088/1361-6455/aa9735, URL: http://stacks.iop.org/0953-4075/51/i=3/a=032003?key=crossref.b59a37cb0b82b4dddffae21223871255.

[29] E. Weckert,
The potential of future light sources to explore the structure and function of matter,
IUCrJ **2** (2015) 230, ISSN: 20522525, DOI: 10.1107/S2052252514024269,
URL: http://www.ncbi.nlm.nih.gov/pubmed/25866660%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4392416.

[30] N. Gazis et al.,
Light Sources in Europe - Case Study: The CompactLight Collaboration,
Instruments **3** (2019) 43, DOI: 10.3390/instruments3030043,
URL: https://www.mdpi.com/2410-390X/3/3/43.

[31] CompactLight Partnership, *CompactLight Project Website*, 2018,
URL: http://www.compactlight.eu/Main/HomePage.

[32] J. Scherer et al., *European IPR Helpdesk: Impact in Horizon 2020 Projects: New Brochure by the European IPR Helpdesk (Eurice GmbH)*, 2018,
URL: https://www.eurice.eu/news/2018/04/11/boosting-impact-in-horizon-2020-projects-new-brochure-by-the-european-ipr-helpdesk/.

[33] Enspire Science, *TRL Scale in Horizon 2020 and ERC - Explained*,
URL: https://enspire.science/trl-scale-horizon-2020-erc-explained/.

[34] V. Shiltsev, *A Phenomenological Cost Model for High Energy Particle Accelerators* (2014), DOI: 10.1088/1748-0221/9/07/T07002,
URL: http://arxiv.org/abs/1404.4097%20http://arxiv.org/abs/1404.4097.

[35] R. Mentzer Morrison,
An Economic Analysis of Electron Accelerators and Cobalt-60 for Irradiating Food, tech. rep., Washington DC: U.S. Department of Agriculture, 1989, p. 48.

[36] Jupiter, *Cost / Benefit Comparison for 45 MeV and 70 MeV Cyclotrons*, tech. rep., Germantown: U.S. Department of Energy, 2005, p. 24.

[37] D. McGinnis, *New Design Approaches for High Intensity Superconducting Linacs - The New ESS Linac Design* (2014) MOYBA02,
DOI: 10.18429/JACOW-IPAC2014-MOYBA02.

[38] Altarelli M et al., *The European X-Ray Free-Electron Laser - Technical design report*, tech. rep., Hamburg: DESY, 2007, p. 646.

[39] P. Lebrun, P. H. Garbincius, *Assessing risk in costing high-energy accelerators: From existing projects to the future linear collider*,
IPAC 2010 - 1st International Particle Accelerator Conference, 2010,
ISBN: 9789290833529.

[40] H.-H. Braun, *PSI's X-ray FEL and its 6 GeV driver linac / ESS-AC Seminar*, Lund, 2017.

[41] A. Humphrey, *SWOT Analysis for Management Consulting. SRI Alumni Newsletter*, 2005.

[42] J. W. Mullins, *The new business road test: what entrepreneurs and executives should do before writing a business plan*, Financial Times Prentice Hall, 2003, p. 270,
ISBN: 0273663569.

[43] A. Osterwalder et al., *Business model generation: a handbook for visionaries, game changers, and challengers*, p. 278, ISBN: 9780470876411.

[44] A. Osterwalder et al.,
Value proposition design: how to create products and services customers want,
ISBN: 9781118968055.

[45] P. R. Garvey, *Analytical Methods for Risk Management*, Chapman and Hall/CRC, 2008,
DOI: 10.1201/9781420011395.

[46] EU-CIRCLE Project, *Risk Assessment Framework*,
URL: http://www.eu-circle.eu/research/key-findings/risk-assessment-framework/.

[47] M. Chorowski, P. Lebrun, G. Riddone,
Preliminary risk analysis of the LHC cryogenic system, tech. rep.

[48] M. Chorowski, P. Lebrun, G. Riddone,
Preliminary Risk Analysis of the LHC Cryogenic System,
Advances in Cryogenic Engineering, Springer US, Boston, MA, 2000, p. 1309.