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2 Synchrotron radiation

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2.1 Synchrotron radiation facilities

Synchrotron radiation facilities are high-brilliance light sources that offer unique possibilities for investigating nature. They provide outstanding tools for both fundamental and applied research and support technology in a wide range of areas. Indeed, synchrotron radiation research has become a major factor in the progress of science and technology in all industrially developed countries. The characteristics of synchrotron radiation are described in detail in Appendix A.

A general overview of the electromagnetic spectrum is presented in Fig. 2.1. Synchrotron radiation light covers the spectrum from infrared and visible through ultraviolet to X-rays.

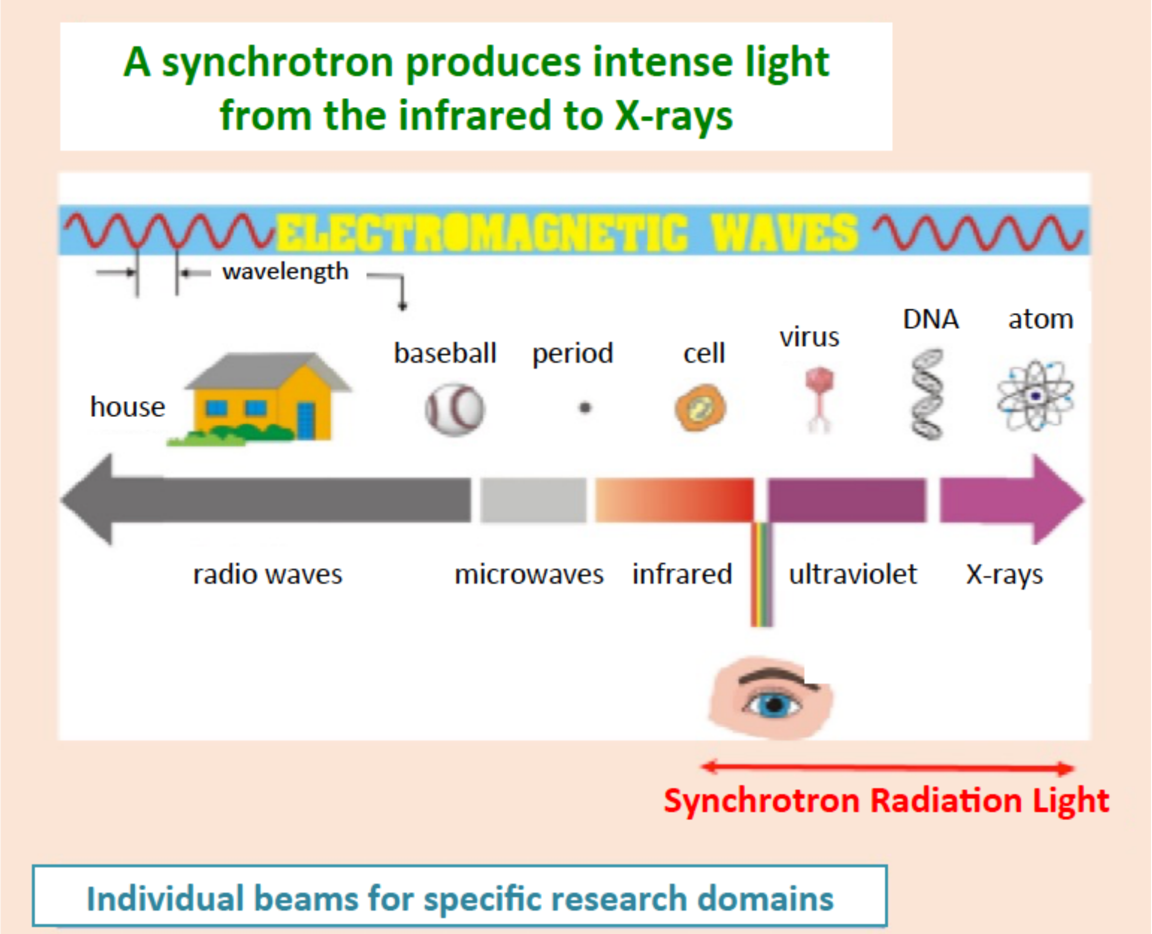

Fig. 2.1: The electromagnetic spectrum from radiation waves to X-rays

More than 60 such light sources exist in the world, with 14 in Europe (Fig. 2.2) [2.1]. While these facilities have much technology in common, each is a unique fit to the needs of its users. Tens of thousands of users in physics, chemistry, materials science, biomedicine, human heritage, technology, and other disciplines utilize these facilities for their research. Experiments with synchrotron light (Fig. 2.3) have produced and continue to produce many landmark results in science and technology. Synchrotron light source facilities offer research capacity for users in almost all universities and research institutes, and increasingly they are playing an essential part in industrial research and development. In Fig. 2.3, just a few examples of research topics that can be investigated with synchrotron radiation are shown. The network of users strongly contributes to a culture of equal opportunities for all researchers, overcoming topical, national, financial, age, and gender barriers.

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The facilities themselves have been continually improved over the years by the introduction of new technologies and adaptation to the specific demands of local user communities. The design of the source and the associated equipment are chosen according to the interests of potential users. Special beam lines can be installed for hard X-rays that are of special interest in structural biology and imaging, whereas infrared beam lines at the other extreme of the spectrum can be used for materials research and archaeology. As a result, no two of these many facilities are identical, but each is adapted to the particular needs of a country or region.

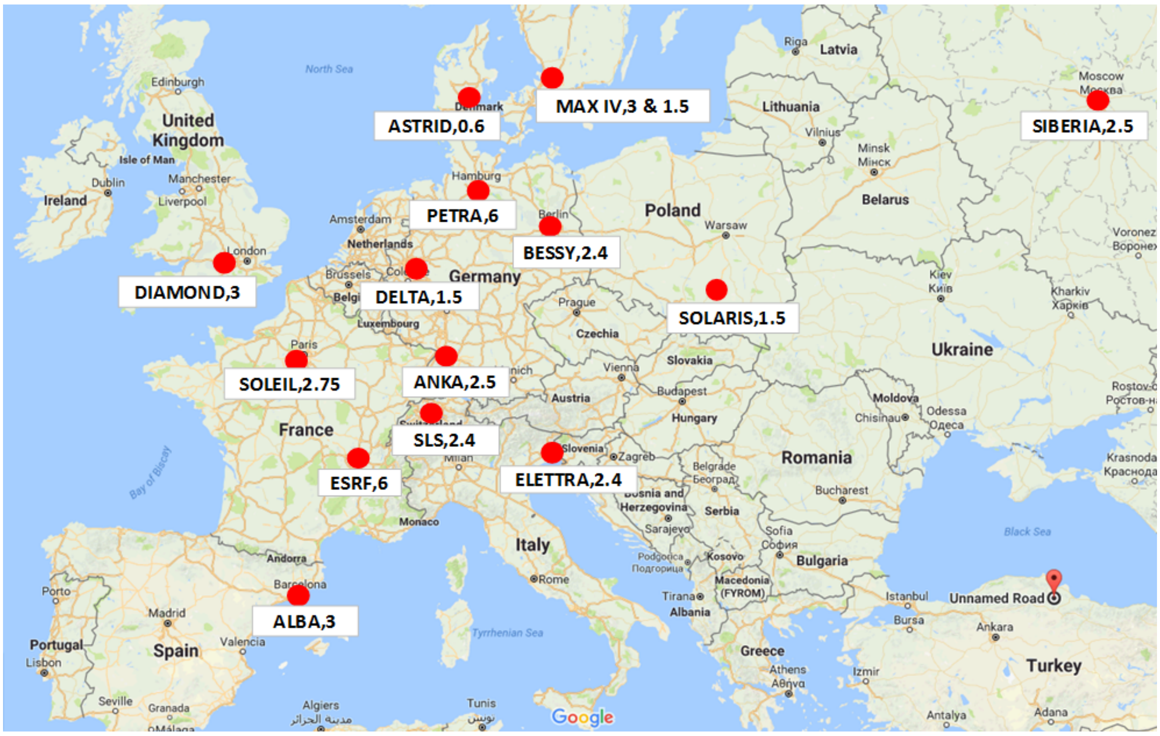
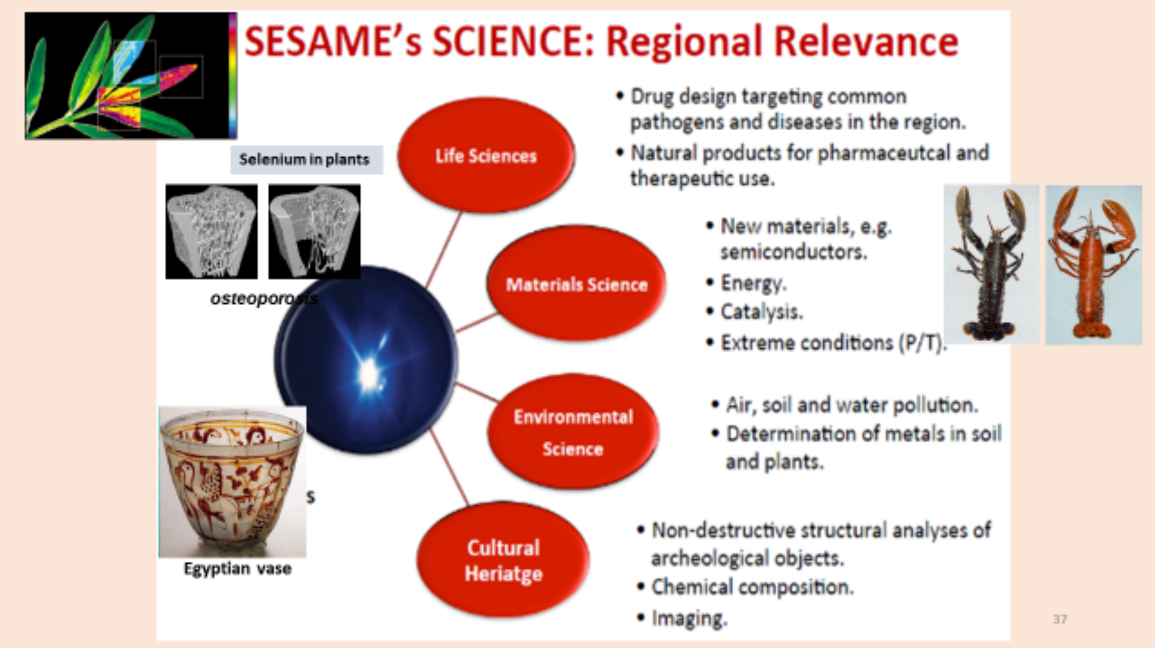


Fig. 2.2: Synchrotron radiation light sources in Europe with energy in GeV



SESAME's SCIENCE: Regional Relevance

Selenium in plants

Life Sciences

- Drug design targeting common pathogens and diseases in the region.
- Natural products for pharmaceutcal and therapeutic use.

osteoporosis

Materials Science

- New materials, e.g. semiconductors.
- Energy.
- Catalysis.
- Extreme conditions (P/T).

Environmental Science

- Air, soil and water pollution.
- Determination of metals in soil and plants.

Egyptian vase

Cultural Heriatge

- Non-destructive structural analyses of archeological objects.
- Chemical composition.
- Imaging.

Fig. 2.3: A selection of research areas that can be investigated with synchrotron radiation

Users of synchrotron light sources from universities, research institutes, and industry will spend relatively short periods of time at the facility. They will prepare the objects to be investigated at their home institutions, put the objects into a special beam at the facility, record the data, and finally do their analyses at home. Transfer of the data will require and stimulate the creation of a powerful digital network and thereby contribute to the regional digital economy. Much of the analysis software is open source, and use of it can lead to collaborations with established experts worldwide.

2.2 Description of a synchrotron light source

The principal layout of a synchrotron radiation light source (SRL) is presented in Fig. 2.4. An SRL consists of two parts: the accelerator complex and the experimental hall with the beam lines.

Synchrotron light is emitted when electrons travelling at close to the speed of light are accelerated by a magnetic field. Because it is costly and difficult to make electrons travel this quickly, it makes sense to accelerate them once and then keep them travelling in a circle so that each time they go around the circle ('ring') they give out light. This is the primary role of the accelerator complex. This 'ring' of electrons allows many (typically 10–40) unique, independent, and purpose-designed laboratories (beam lines) to be positioned around the ring within a single experimental hall.

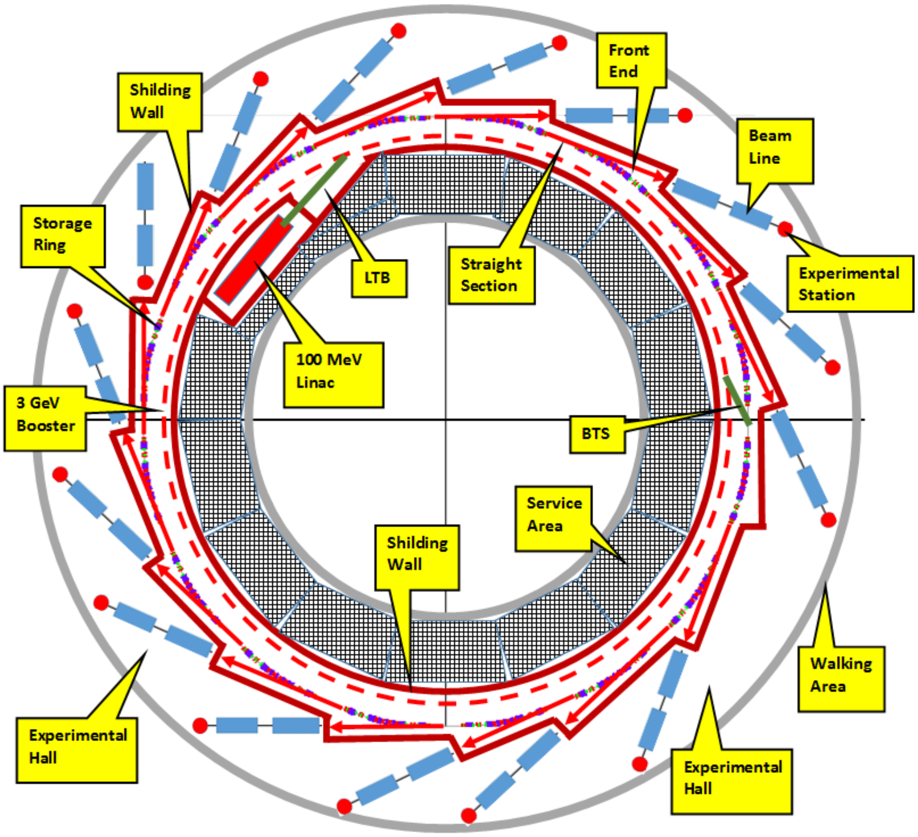


Fig. 2.4: Layout of a synchrotron light source facility

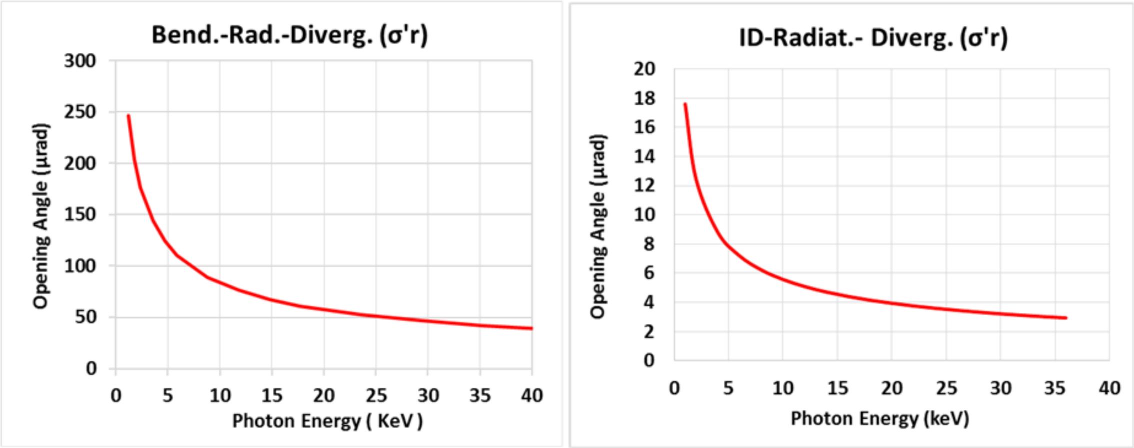


Fig. 2.5: The opening of the synchrotron radiation cone from the bending magnet (left-hand side) and the insertion device radiation (right-hand side).

To achieve the necessary high energies, the electrons must be accelerated in steps. First, they are accelerated in a linear accelerator (linac) up to about 100 MeV; then they are transferred (via a linac-to-booster transfer line, LTB) to a booster synchrotron where they are accelerated to the final storage ring energy; finally they are sent (via a booster-to-storage ring transfer line, BTS) to the storage ring, where huge numbers (typically many billions) of electrons accumulate to give very intense light. Since the electrons constantly lose energy through the emission of storage ring (SR) light, these losses must be compensated continuously by high-frequency electromagnetic fields using accelerating cavities. The electrons always travel in tubes evacuated to ultra-low pressures, the so-called vacuum system. To keep the electrons together, special focusing magnets have to be introduced between the bending magnets. The magnet system together with the high-frequency system and the vacuum system form a rather complicated arrangement with many possibilities of being adapted for cost-to-performance optimization. The storage ring consists of a series of so-called achromats (up to 30 and possibly more). The technical arrangements of the different components are the same within all achromats. Straight sections with a length of several metres connect the achromats. These straight sections accommodate the insertion devices for producing radiation with a special high brilliance which is tailored to each beam line (see Fig. 2.5); the details are described in Appendix A.

Synchrotron radiation is emitted when a relativistic electron beam is deflected in the bending magnets or in insertion devices (see Fig. 2.5). The spectral range of energy of the photon beams originating at these devices is extremely broad: from infrared through ultraviolet up to hard X-rays (Fig. 2.6). This is one of the properties that make SRLs so attractive, besides the enormous intensity they provide. From the insertion devices and bending magnets the light is transported by specially designed front ends and beam lines to the experimental hatch in the experimental hall. These beam lines will have very different properties depending on the scientific questions to be studied. However, in most cases they will include mirrors and a monochromator, which will select the most appropriate wavelength in the broad spectrum and focus it onto the sample. Some beam lines are very simple, whereas the construction of others can be quite demanding technical projects. As one example, the layout of a beam line used for X-ray absorption spectroscopy with an overall length of 35 m is displayed in Fig. 2.7.

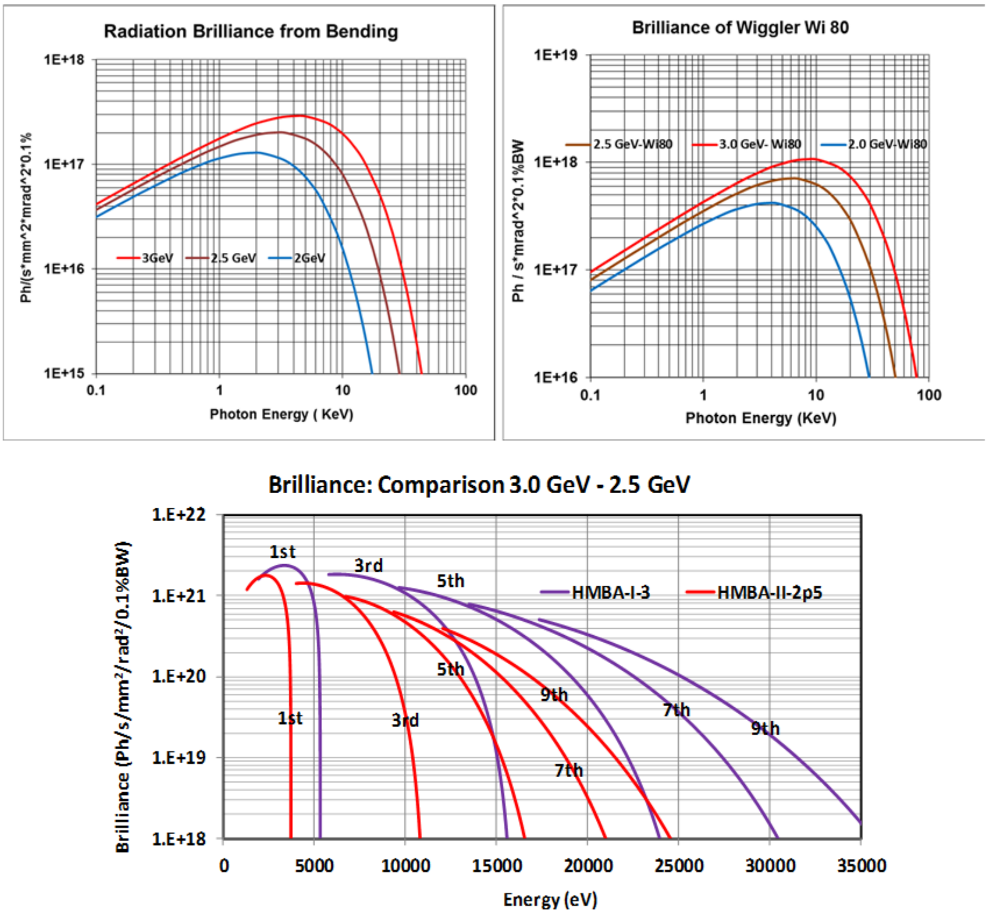


Fig. 2.6: Synchrotron radiation brilliance emitted from a relativistic beam deflected in a bending magnet and wiggler (above) and in an insertion device (below).

Synchrotron light facilities are often used as super-microscopes to explore the structure of matter at scales down to the diameters of atoms or below. In such applications the spatial resolution of the radiation is extremely important; this is the smallest distance that can still be resolved. The spatial resolution is largely determined by the geometrical properties of the circulating electron beam, in particular the cross-section and angular divergence of the beam. The smaller both are, the better the resolution in the experiments will be. To characterize the quality of the electron beam, various parameters are used that essentially boil down to the product of the beam cross-section and the angular divergence; this product is called the *emittance* of the beam and is constant around the ring. The emittance depends on the design of the magnets of the electron accelerator and cannot be changed later.

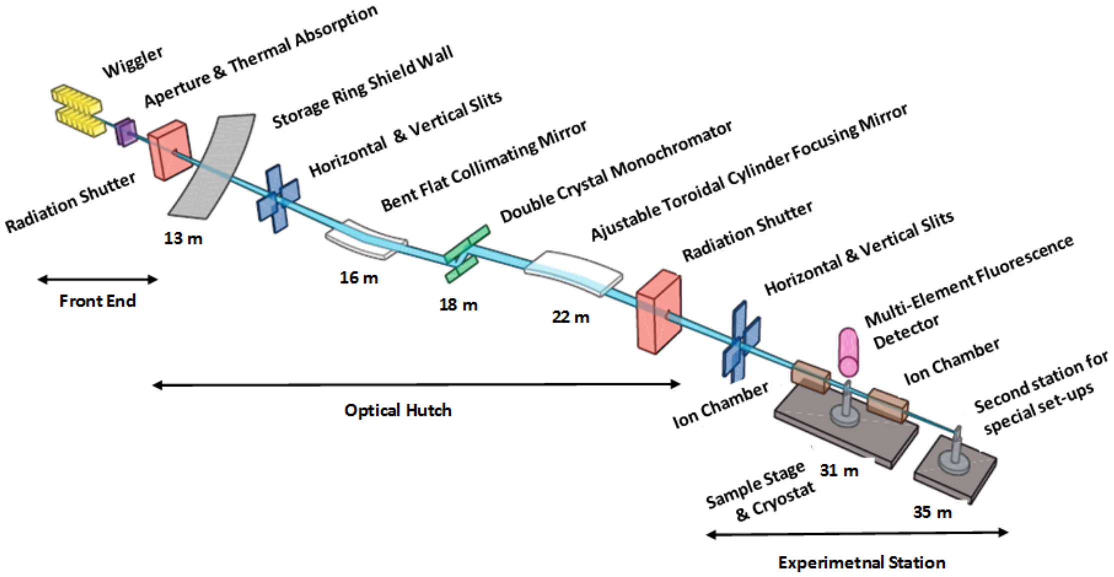


Fig. 2.7: Layout of the X-ray absorption spectroscopy (XAS) beamline at the Australian SRL [2.2]

SRLs offer another possibility, which makes them extremely attractive and versatile as research instruments. If the straight insertions are properly designed, special devices can be installed between the bending magnets. These so-called insertion devices are called *wigglers* or *undulators* and can produce light beams with special characteristics chosen according to the requirements of users. The most recent facilities built (e.g. MAX IV at Lund [2.3]) were designed to give high priority to such beam properties and not so much to higher electron energies. They are called '4th generation light sources'.

Thus, a synchrotron radiation facility is characterized by a number of parameters which can be chosen by taking into account the interests of potential users, optimization of construction and operation costs, the know-how of future staff, and other general aspects. Selecting these parameters is the first major task in preparing a final design.

2.3 Scientific case and selection of beam lines

The proposal to build a SEE International Institute for Sustainable Technology (SEEIIST) is utterly compelling when one considers the benefit to the people of the region. However, the case for building SEEIIST rests ultimately upon the value of the science and technology and the range of areas on which it can have an impact. The value of the project is expected to be realized for the SEE region over an extended period of time.

Worldwide, SRLs provide illuminating and essential insights which extend to virtually all aspects of scientific activity, but for every existing facility a proposal has been made on the basis of the particular needs of the community it serves. No single facility can cover every application. Therefore, a goal of the SEEIIST must be to establish itself as a partner in the international network of synchrotrons. One way of achieving this is through participating in the League of European Accelerator-based Photon Sources (LEAPS, https://www.leaps-initiative.eu/) [2.4], a consortium of 13 synchrotrons and three free electron lasers across Europe.

Furthermore, because the first part of the project will involve constructing the storage ring and building regional capacity, it is envisaged that from day one there will be a small number of operating beam lines (applications laboratories). Over a longer period of time, perhaps a decade, new beam lines will be built which would allow the facility to grow to full maturity and capacity. A process for choosing beam lines will be established which takes into account the needs of all stakeholders in SEE countries. Before then, three very general technical themes can be identified for which synchrotron light would offer exciting opportunities [2.5]. These are summarized here and analysed in more detail in the next section.

- **Spectroscopy** [2.6] with X-rays can only be carried out at synchrotron facilities. It has applications spanning physics, chemistry, surface science, nanoscale science, biological science, environmental and earth sciences, and other areas ranging from the fundamental to the industrial. Cultural heritage and conservation science can also benefit from access to this tool. X-ray spectroscopy is a non-destructive, chemically selective tool with a large user community and is a core capacity which is greatly oversubscribed worldwide.
- **Imaging** [2.7]: the first recorded X-ray image was of the hand of Roentgen's wife in 1895; since that time, imaging has become synonymous with X-rays. The past two decades have seen revolutions in X-ray imaging which have made it possible to image nanometre-sized structures in 3D. With synchrotron light it is possible to image in exquisite detail; examples include processes—in real time—of technological importance (e.g. welding, corrosion, 3D printing), biomaterials (e.g. bone, arterioskeletal disease, plants), soil and earth science samples, and cultural heritage objects.
- **Structure** [2.8, 2.9]: X-rays provide the pre-eminent tool for determining the structure of matter at an atomic scale. Synchrotron light allows the structure of large molecules relevant to human health and wellbeing (such as viruses and proteins) to be determined in a matter of minutes, and it has become an integral part of the pharmaceutical industry and life sciences research. Synchrotron light is of equal importance in physics, materials science, and materials chemistry, in which it plays a key role in the development of new battery materials, energy conservation, green industrial processes, and bioengineering.

The vision is of an institute which will train and retain the next generation of scientists and technologists within the SEE region. But it can do much more than this; it can reverse the tide of migration of talent away from the region in recent years. In the early years of the institute most staff will have been trained outside the region and be returning home. SEE-LS will have unique appealing aspects which will, without doubt, attract scientists from across the world and establish the SEE region as a zone of excellence.

2.3.1 Considerations of likely scientific fields for SEEIIST

When considering what beam lines should be built, it is possible to analyse the choices in many ways; the most powerful and compelling consideration is the scientific areas that will be enhanced. With a few notable exceptions, beam lines serve a wide community, and every community can benefit from access to a broad portfolio of beam lines. Indeed, one of the most powerful features of synchrotron light sources is that they are science led; often users first come to a facility to use one technique, but then their work flourishes in novel directions from having access to a broad range of different techniques. Knowledge transfer across disciplines, national borders, and generations is an intrinsic feature of synchrotron light sources.

Because support for a synchrotron light source must come primarily from those who will use the source, it is essential to consider what the major groups of users are likely to need. The SEE science community, although unique, must surely have much in common with user communities worldwide, and so it is helpful to consider briefly the needs of five major science and technology groupings which are commonly identified in Europe.

2.3.1.1 Integrated structural biology and the medical and life sciences

Ever since the determination of the structure of DNA, structural biology has become increasingly important. Knowledge of the atomic structure of the functional components of cells is now recognized to be a fundamental factor in understanding and curing major diseases. Use of SRLs is an essential way in which pharmaceutical companies develop new drugs. In Europe, structural biologists form the largest single group of SRL users. This group of users has very clear requirements of synchrotron facilities. They demand just-in-time access to facilities which have become highly automated and very sophisticated. The key technique they use is X-ray diffraction for carrying out macromolecular crystallography (MX). There are many such facilities currently available in Europe, and these facilities compete to host the most competitive science projects. For this reason, a careful analysis will be needed of the current strengths and requirements of the SEE structural biology community to discern whether there is already sufficient access to MX facilities elsewhere in Europe or whether construction of a SEE MX beam line is a necessary part of a coherent development plan.

Although knowledge of structure at an atomic level (at Å to nm length scales) is the core requirement of integrated structural biology, it is insufficient for a full understanding of the biological components, and tools are needed for determining how the components function in partnership at larger length scales (nm to μm). Synchrotron facilities provide two classes of tools: small-angle scattering and imaging. Small-angle scattering is used to find out how complexes assemble on the 10−500 nm length scale, and imaging now extends from the millimetre scale down to less than 20 nm. Beam lines that have such capabilities are among the most highly oversubscribed in Europe and would be strong contenders for inclusion within the initial portfolio.

2.3.1.2 Chemistry and catalysis

Chemistry plays a major role in all developed economies worldwide, being responsible for as much as 5% of global GDP, and it has been said that about 90% of all chemical processes involve the use of a catalyst. The development of new processes is a key part of ongoing efforts to find novel ways of making the feedstock of current chemicals from sustainable sources and to use feedstocks from renewable sources to make entirely new alternatives to materials that currently necessitate the exploitation of non-renewable resources. The long-term vision is to be able to design catalysts specific to every process. Research in chemistry and catalysis has benefited enormously from the availability of synchrotron facilities. Decades ago, model systems were studied *ex situ* under idealized conditions (e.g. ultra-high vacuum, single crystals), but in recent years it has become normal to study systems under *operando* conditions of high temperature and pressure and complexity of composition and form.

Furthermore, it is now recognized that it is essential to be able to employ a number of different techniques under the same conditions. For example, it is vital to know the chemical state of a catalyst at the atomic level, but also to know how this interacts with the meso- and long-range structure. This can be achieved by using a combination of spectroscopic and diffraction tools (atomic-level structure), small-angle scattering (meso-structure), and imaging (long-range and system-level structure). Finally, these techniques must be developed alongside and with the analytical techniques found in a modern chemical laboratory. It is envisaged that SEE-LS will facilitate collaborations between existing SEE institutions to create a world-competitive centre for chemistry and catalysis which will benefit the whole region.

2.3.1.3 Engineering and materials science

The SEE nations have a long history of engineering, but in recent decades the economic fortunes of the engineering sector have suffered because of political turmoil and fierce competition from emerging economies [2.10, 2.11]. It is widely recognized that pre-eminence in the fields of engineering and materials science is a key factor for any nation wishing to sustain (or regain) economic competitiveness and move towards a model of sustainable economic growth. Engineering is both a discipline and a system of processes whereby materials are transformed into objects of practical, social, and economic value. The range of applications of engineering is massive, spanning enormous length scales, from bridges and aircraft to micro-miniature, even nanoscale, machines. Engineering was once mostly concerned with the processes by which objects are formed (e.g. casting, machining, welding). However, in a world in which sustainability is of increasing importance, it is vital to consider the whole life cycle of manufactured objects, encompassing their birth (e.g. deposition, casting, sintering, fabrication), use (e.g. behaviour under load or in gas conditions), death (e.g. failure, corrosion), and finally recycling (making objects suitable for reuse and preventing environmental pollution). Synchrotrons provide valuable tools for every stage of the engineering life cycle.

Engineered objects are usually complex because they rely on properties of one part interacting with and improving the performance of other parts for the benefit of the whole. In the past it was essential to take an object apart to understand the detailed properties of its constituent parts. However, in modern engineering synchrotrons have made it possible to use X-rays for imaging and diffraction from the nano- to the macro-scale; in particular, the intensity of X-rays is sufficient to penetrate the whole object to be investigated over the full range of length scales needed to understand its detailed properties. It is possible to study materials while they are being formed (i.e. during casting, welding, or additive manufacturing), and subsequently stresses can be measured in working objects (such as a prosthesis).

Development of new materials lies at the foundation of societies' attempts to meet the challenges in rebuilding their manufacturing industries for future low-carbon and sustainable-energy economies. Synchrotron light sources provide facilities of the highest quality and broadest portfolios available for understanding materials. Time matters in a competitive world, and synchrotrons can offer significant and unique advantages in the development cycle of materials, because both measurement and interpretation can be swift and timely. Automation is becoming increasingly important at mature synchrotron facilities; it is the universal hallmark of the working protocols within integrated structural biology, and methods of automation are being transferred to other disciplines such as materials development (for engineering and also chemistry). However, before automation can be implemented, it is necessary for industries and users within the SEE region to determine what measurements are needed most frequently and most urgently within the region. A step-by-step approach to automation, led by the unique blend of needs within the region, is essential. The long-term goal is to provide laboratories in nations distant from a synchrotron facility the same or even better quality of experience as facilities in their home institution.

2.3.1.4 Condensed matter physics

There can be no doubt that research into solid state physics has utterly transformed the world we live in, because it is the discoveries in this discipline that have led to the creation of all modern methods of digital communication and made possible the computing revolution—from the first computer which took up a whole room to ubiquitous pocket-sized supercomputers (smart phones). It is a fact that esoteric concepts in condensed matter physics have paved the way for the leaps in technology which have made the lifestyles of today possible.

It remains true that the frontiers of physics are very hard to explain to non-experts and that immense efforts continue to be expended to understand and develop materials with new properties. But there are common threads within this endeavour. The thread which is most common is an understanding that the electronic properties of materials depend on the precise positioning of atoms with specific properties and that the subtle interplay that takes place when individual atoms are brought together produces new collective phenomena in magnetism, electronic structure, and electron dynamics. These collective behaviours are influenced by nanostructure quantum fluctuations, giving hints of new states of matter. This area of fundamental physics offers the prospect of constructing practical quantum computers—the next paradigm shift in computing technology.

Condensed matter physics requires tools for determining where atoms are and their chemical, magnetic, and electronic states. Synchrotrons provide an extensive suite of tools to support condensed matter physics. Some of the tools, such as diffraction and X-ray spectroscopy, are in common with other areas, and condensed matter physicists would share access to the facilities according to need (and competitive peer review). Other tools may be dedicated to condensed matter physics; these beam lines tend to employ low-energy (20−1000 eV) X-rays or so-called tender X-rays (500–3000 eV) for two reasons. Firstly, the energies of these X-rays are sufficient only to excite and probe the valence (or outermost) electrons of matter, which are predominantly responsible for the physical properties being studied; secondly, X-rays with these energies can penetrate only a short distance into matter. This is important because the behaviour of many advanced materials is determined by the structure of the outermost few layers of atoms. Information provided by such soft X-rays is not obstructed by signals from the bulk. Another technique of beam lines dedicated to the study of condensed matter physics is X-ray photoelectron spectroscopy, which makes it possible to study the structure of the electrons in matter that are responsible for all the key properties of interest in solid state physics, for example high-temperature superconductivity and critical quantum behaviours. Such facilities can help bring together advances in theory and the development of new materials, which when combined will pave the way for breakthroughs that can transform the digital world as we know it.

2.3.1.5 Environmental and earth sciences and cultural heritage

The SEE region, in common with the rest of Europe, is facing enormous environmental challenges in the context of finite or diminishing resources coupled with growing and changing economic needs. At the same time, human populations and the demands they make on the environment are causing increasing damage to the atmosphere, water, and soil. A major challenge facing society is to identify and use natural resources in the most sustainable way possible and, in recognition of the harm done in ages past, to engage in environmental remediation wherever possible [2.12].

Spatial and chemical heterogeneity and complexity are universal hallmarks of the minerals, soils, and fluids studied in the environmental and earth sciences. For example, soils are structures made up of various minerals, biomaterials, plants, bacteria, and soil-dwelling animals (e.g. worms). This structural complexity is critical to the proper functioning of soil. Trace elements are an essential part of soil, but regrettably many soil environments have been spoilt as a consequence of past industrial activity. There are many places in the SEE where the soil has been damaged by mining, extraction, and energy generation [2.13]. Synchrotrons provide a uniquely useful suite of tools to assist in knowledge-based remediation (rather than bury-and-forget) policies. X-ray spectroscopy combined with imaging makes it possible to determine not only where and how contaminants are distributed in the soil environment but also, most importantly, the chemical state of each contaminant. This knowledge is absolutely key in helping to decide how best to remove contaminants. It is now possible to measure chemical speciation for concentrations as low as a few ppm in situ.

Nanomaterials are finding increasing use in the modern world because they can offer special advantageous properties compared with bulk materials; however, nanomaterials may cause environmental problems when they are disposed of after use. This is becoming a growing issue of concern in the 21st century as surprisingly large quantities of nanomaterials are being used and yet comparatively little consideration has been given to their effects on the environment. This is a challenge that modern synchrotrons can help with: the latest generation of scanning X-ray microscopes are capable of resolving length scales as small as 10 nm [2.14], which when combined with spectroscopy makes it possible to follow the chemical pathways of nanomaterial pollutants in the environment.

Steady supplies of minerals and other elements remain important to the economic security of a region, and so the search for new and secure supplies and better methods of extraction will continue across the SEE region. The ability of synchrotron-based spectroscopy to determine the chemical states of important elements at low concentrations will be vital in such endeavours. In addition, improvement in extraction methods requires deep understanding of the structure of materials. For a complex material, gaining such understanding is made simpler by the use of diffraction combined with imaging techniques afforded by synchrotrons. Finally, processes of extraction can be modelled under operational conditions by building upon the techniques developed for chemical catalysis described in section 2.3.1.2 above.

The SEE countries have a cultural heritage which matches—and in many places surpasses—that found elsewhere in Europe. Understanding this heritage is of enormous interest to the people of the region, and synchrotrons provide powerful tools which make it possible to look deep inside fragile and uniquely valuable cultural objects to determine their provenance and aid in their conservation. There are now examples within Europe of how national and regional synchrotron facilities can collaborate with people in charge of the conservation of cultural heritage to build capacity that is uniquely equipped to meet the specific needs of a region. Currently no facility in Europe is designed to meet the needs of the unique SEE region, and so compromises are inevitable. Therefore, the construction of SEE-LS will provide opportunities to bring together conservationists and experts in building synchrotron facilities to create an institution that will promote understanding and facilitate conservation of the cultural heritage of the SEE for the next generation.

2.4 Design parameters of the SEE light source

The more than 60 SRL facilities in the world have energies in the range of 0.5–3 GeV. Most users are particularly interested in X-rays, and the energy spectrum of the X-rays depends on the maximum electron energy of the storage ring. Facilities with electron energies below 2 GeV will emit mainly soft X-rays with a spectrum up to 10 keV. Electrons with energies of around 3 GeV emit radiation in the hard X-ray regime, up to 30 keV.

Many users (mainly those interested in structural molecular research) want to have hard X-rays; therefore most of the latest SRLs are 3 GeV machines that produce hard X-rays. Because the cost of these facilities rises sharply with energy, one might consider a first-stage facility in SEE with an energy of 2.5 GeV. This would save on initial investment while allowing for a later upgrade to 3 GeV by adding additional radio-frequency power.

Also of importance to users is the brilliance of the SRL, which is the number of emitted photons normalized with respect to the radiation opening angle and area (see Fig. 2.5). The brilliance is inversely proportional to the emittance and proportional to the stored electron current. The emittance is in general proportional to the third power of the deflection angle of the bending magnets. Hence, to obtain a small emittance, it is much better to install a greater number of short bending magnets instead of a few long magnets. This is one of the elements of the new concept of MAX IV [2.14]. Furthermore, the highest brilliances are obtained from insertion devices that are located in the straight sections. To take advantage of this fact and to enable many beam lines from insertion devices, the storage ring should be designed with a sufficient number of straight sections. In addition, it is expected that in the future more users will be looking for a higher degree of *radiation coherence* in order to open up new areas of application of synchrotron radiation. The coherence increases with smaller emittance as well. Figure 2.8 shows the coherence of the light from 3rd generation (emittance = 4 nm rad) and 4th generation (emittance = 0.2 nm rad) light sources. Going from a 3rd to 4th generation light source, the coherence increases by more than an order of magnitude. Sources that combine all of these aspects—an emittance smaller than 300 pm rad, a large number of straight sections, and a high degree of coherence—are called 4th generation light sources.

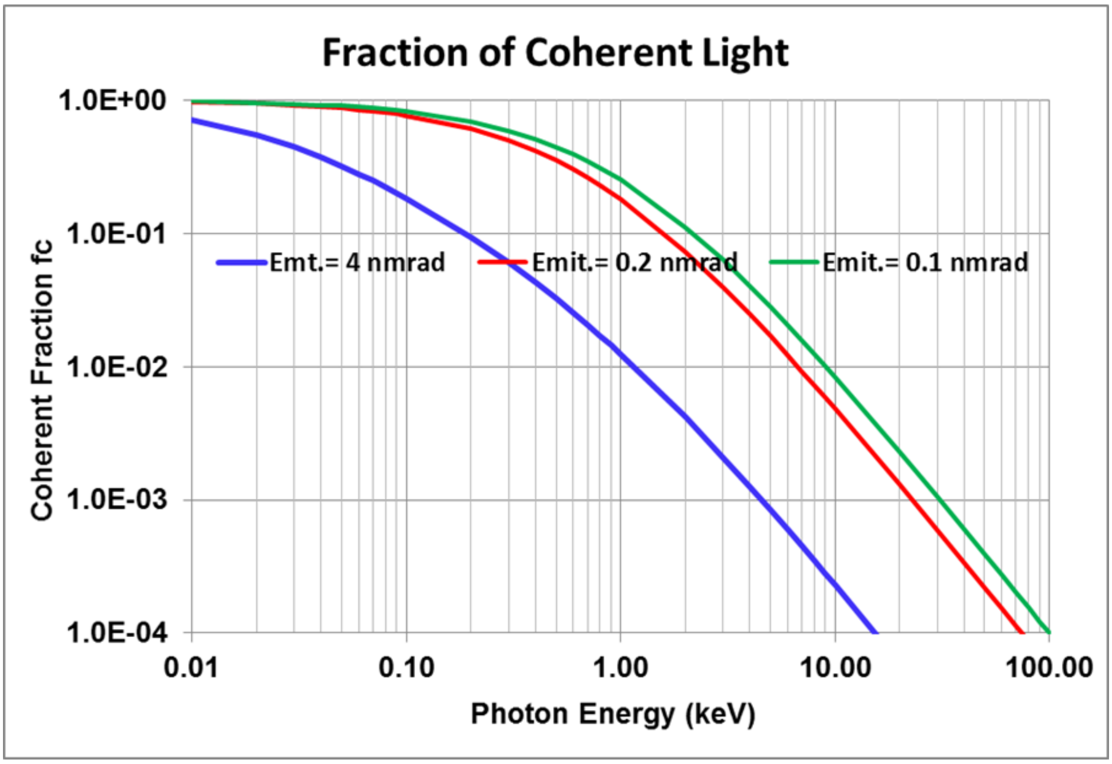


Fig. 2.8: The fraction of coherent light as a function of the photon energy

In order to be fully competitive, the SEE-LS project should be a 4th generation light source. Keeping in mind the aspects mentioned above, preliminary studies have shown that the following parameters would offer an attractive compromise between excellent performance and reasonable cost: energy of 2.5 GeV (with a possibility of upgrading to 3 GeV), emittance of less than 200 pmrad, circumference no larger than 350 m to save on investment costs, a magnet lattice with 16 straight sections for the installation of insertion devices, and a current of 400–500 mA in the machine.

Different types of lattices have been investigated to see which can meet these requirements of a 4th generation light source: a 7 multi-bend achromat (7MBA), as for MAX IV [2.14] and the upgrade of SLS; a double triplet achromat (DTBA), as for the upgrade of Diamond [2.15] and ELETTRA [2.16]; and a hybrid multi-bend achromat (HMBA), as for the ESRF-EBS [2.16] and the upgrade of APS [2.18] and other machines. The result is that a solution based on the HMBA lattice but incorporating some new ideas can satisfy the required criteria for the SEE-LS. For the different components and subsystems, the best proven technology will be used in order to minimize cost and risk. This will produce a state-of-the-art facility that is world-leading in some respects. The overall capacity for beam lines will be up to 14 insertion devices (10 undulators, two wigglers, and two superconducting wigglers). In addition, several bending magnet beam lines (up to 16) can be constructed. The choice of the beam lines to be installed initially would, of course, depend on the interest of users.

The proposed design is unique in the sense that it combines the best techniques of previous facilities, such as the magnets from the European Synchrotron Radiation Facility (ESRF) [2.17] and the vacuum and radio-frequency system from the MAX IV laboratory [2.14].

The injector will use a 100 MeV linac as pre-injector together with a full-energy booster synchrotron. The 100 MeV linac will be a commercial one, while the booster synchrotron will have to be designed and built by SEE-LS. The booster synchrotron will be located in the machine tunnel to save on costs and to obtain a small emittance so as to reduce electron losses during injection, minimize the shielding around the storage ring, and increase the injection efficiency.

The accelerator complex should fulfil the following requirements.

i) It should have high flux over a wide energy range, from carbon (K-edge = 285 eV) for scanning transmission X-ray microscopy (STXM) to palladium (K-edge = 24.4 keV) for extended X-ray absorption fine structure (EXAFS).

ii) It should have high brightness over a more limited range, from carbon (K-edge = 285 eV) for STXM to selenium (K-edge = 12.6 keV) for multi-wavelength anomalous diffraction (MAD) in protein crystallography.

iii) In case higher-energy X-rays (> 25 keV) are needed (e.g. tomography on thick samples, EXAFS on $Z > 46$ elements), it will suffice to later install moderate-flux and low-brightness beam lines based on few-pole wigglers.

iv) It should have sufficient straight sections for insertion device-based beam lines, which probably means 12- or 16-fold periodicity. The only foreseeable need for bending magnet beam lines is for electron beam diagnostics, and possibly one or two infrared beam lines.

v) An emittance of 200 pm rad is possible for the most ambitious facilities at present and will thus be the goal of a less ambitious facility to be completed in around 10 years from now.

vi) Since ultra-fast experiments are not prioritized, the radio-frequency system can be chosen to maximize brightness and reliability while minimizing cost. A 100 MHz system based on commercial frequency-modulation technology seems a reasonable starting point.

vii) It should have a 300–350 m circumference accommodating 12–16 straight sections with insertion device beam lines only. Bend magnet beam lines should be made available for diagnostic purposes and for one or two infrared beam lines.

viii) It should have a ring energy of around 2.5–3.0 GeV so that high brightness is achieved over a photon energy range from carbon (K-edge = 285 eV) for STXM to selenium (K-edge = 12.6 keV) for protein crystallography (MAD). High flux should be provided up to palladium (K-edge = 24.4 keV). For energies above 20 keV or so, this might be best achieved using multi-pole wigglers.

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