Synchrotron Light Sources and Free-Electron Lasers

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Jochen R. Schneider • Jerome B. Hastings
Editors

Synchrotron Light Sources and Free-Electron Lasers

Accelerator Physics, Instrumentation and Science Applications

With 782 Figures and 54 Tables

Springer Reference

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Preface

Hardly any discovery of the nineteenth century has had a greater impact on science and technology than that of Wilhelm Conrad Röntgen's seminal discovery of the X-rays. X-ray tube-based instruments soon made their way into numerous applications in medicine, materials science, chemistry, biology, and public security. Research with X-rays experienced a stunning boost after the discovery of synchrotron radiation in 1946 and the start of active research about 50 years ago at synchrotrons and in turn electron/positron storage rings originally built to serve the needs of particle physics. Synchrotron radiation covers the spectral range from terahertz and infrared to UV and hard X-rays, and its properties can be calculated in great detail. The radiation is highly collimated, linearly polarized, and very intense; its wavelength is continuously tunable over large spectral ranges. For planning experiments, the most important figure of merit to assess an X-ray source is its brightness, often also called brilliance, which is the photon flux normalized to the solid angle of emission, the source size, and an energy band. Due to the immense progress in accelerator physics and technology, the brightness of synchrotron radiation sources has increased by about 3 orders of magnitude every 10 years, which corresponds to a slope steeper than Moore's law developed to describe the expected progress in information technology. Electron or positron storage rings are used all over the world to provide synchrotron radiation, and more and more dedicated synchrotron radiation facilities have been and are being built in order to satisfy an ever-growing demand for beamtime. Based upon recent estimates, the user community includes up to 50,000 people worldwide who are pursuing a wide range of applications in basic and applied sciences. New facilities have provided better X-ray beams and opened the field to new research areas like paleontology and cultural heritage. As an example, very detailed images of tiny insects enclosed in opaque amber and unseen by the eye for 100 million years have been reconstructed in great detail from phase contrast images taken with hard X-rays at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. Probably the most striking success story in synchrotron radiation research is protein crystallography, where about 70,000 structures determined with synchrotron radiation have been deposited in the protein data bank to date. Since 1997, five

Nobel Prizes in chemistry have been awarded to discoveries which could only be achieved by using synchrotron radiation.

Modern storage ring facilities provide high-brightness beams with a significant degree of spatial coherence which has allowed the development of novel imaging methods. Strong efforts are made to improve the time resolution of pump-probe experiments at storage rings; however, the possibilities are limited to 10's of picoseconds. Here the free-electron lasers (FELs) make the difference. They provide extremely intense, spatially coherent radiation in very short pulses. Pulses between $\sim$10 fs and 50 fs duration contain as many soft or hard X-ray photons as one can get in 1 second at a modern storage ring facility. This corresponds to an increase in peak brightness by about 10 orders of magnitude and opens for the first time the possibility to study matter at its intrinsic length and time scales, which is angstroms and femtoseconds, respectively. The development of FELs goes back to work by J. M. J. Madey[1] on stimulated emission of bremsstrahlung in a periodic magnetic field in 1970. Madey was the first who predicted laser-like radiation in the far-infrared and visible spectral range and later built the first FEL. In the 1980s, a scheme for high-gain soft and hard X-ray free-electron lasers was proposed[2,3], and the first soft X-ray FEL user facility FLASH at DESY in Hamburg started operation in 2005 with the first hard X-ray FEL, the Linear Coherent Light Source (LCLS) at Stanford, beginning in 2009. FERMI @Elettra is the first externally seeded FEL so far operating in the VUV, and in Japan the hard X-ray FEL SACLA has been in operation since 2011. More FELs are in an advanced planning stage or under construction worldwide. The progress made with the FEL facilities in operation is breathtaking, and on the user side a very significant number of groundbreaking experiments have been performed.

Whereas at FELs each pulse should be characterized shot by shot, modern storage ring synchrotron radiation facilities are characterized by outstanding beam stability and operational reliability. New storage ring lattices have been suggested and are realized at new facilities like MAX IV in Lund, Sweden, and Sirius in Campinas, Brazil, or in extensive upgrades of some of the existing hard X-ray facilities, for example, the ESRF in Grenoble, which will increase the brightness by almost two orders of magnitude. Triggered by the needs of the X-ray FELs, better X-ray optical components and new detector systems have been developed, which will help experiments to make full use of the outstanding beam characteristics of the new storage rings. Altogether progress in accelerator-driven light sources and X-ray science continues at an extremely rapid pace, and the Springer Reference on Synchrotron Radiation and Free-Electron Lasers intends to keep the diverse synchrotron radiation and laser communities informed about progress in both accelerator development and novel applications of these light sources. Because the

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[1] J.M.J. Madey, J. Appl. Phys. **42**, 1906 (1971)

[2] A.M. Kondratenko, E.L. Saldin, Part. Accelerators **10**, 207 (1980)

[3] R. Bonifacio, C. Pellegrini, L.M. Narduci, Opt. Communications **50**, 373 (1984)

Springer Reference is accessible online, the authors of the different chapters have the opportunity to update their respective contributions to reflect new developments in the field. The reader will have access to all versions of the chapter. For the same reason the editors will continue to invite authors to write contributions which will be available to the public shortly after acceptance. The issue of the Springer Reference on hand should therefore be considered as the start of an ongoing process. Its flexibility fits perfectly to a research field which develops as fast as X-ray science does today.

The contributions in the first edition of the Reference are arranged in 9 parts. We start with an introduction to the production of synchrotron radiation and its characteristics followed by an overview on recent work aiming toward shorter X-ray pulses from storage rings and an introduction to the generation mechanisms of terahertz radiation. Next, the theory of high-gain free-electron lasers is introduced followed by descriptions of self-seeding of FELs based on self-amplified spontaneous emission (SASE) and externally seeded harmonic generation. The section ends with a discussion of new opportunities for high-brightness X-ray sources driven by laser-plasma accelerators.

The second section deals with facilities and their design and starts with general discussions on low-emittance storage rings. Three chapters on soft and hard X-ray single-pass high-gain free-electron lasers show the enormous progress made in understanding and building FELs driven by linear accelerators. Linac operation can become more efficient when recovering the electron energy. The scheme of energy recovery linacs (ERLs) is described in the last chapter of this section.

The following section highlights progress in accelerator technology and starts with the description of an integrated multi-magnet system improving the emittance of storage rings by orders of magnitude. Next, superconducting RF and high-brightness photoinjectors for linac-driven light sources are presented as enabling technologies for the new accelerator-driven light sources. The contribution thereafter deals with coupled-bunch instabilities and their effect on accelerator operation and performance. In general, reliability and stability of storage rings and FELs very much depend on effective control systems and adequate operational tools as well as on beam instrumentation and diagnostics. These items are discussed in the three contributions which conclude the third section.

The remaining part of the book focuses on preparing soft and hard X-ray beams for experiments and using them for various scientific applications. We start with a section on producing, characterization, and handling of these beams with a chapter on shaping photon beams with undulators and wigglers, technologies which pushed the brightness of third-generation storage ring facilities by orders of magnitude and which are also of key importance for free-electron lasers. Next, ways to describe the coherence properties of high-brightness X-ray beams and methods to determine their wave front characteristics are discussed, followed by chapters on the characterization of the time structure of FEL radiation and on split-delay units, which improve the time resolution in certain pump-probe experiments dramatically. Finally, progress in preparing high-quality focusing mirrors for coherent hard X-ray beams and perfect crystal optics is presented.

X-ray detectors, especially area detectors, have been a bottleneck in the development of X-ray science for many years. Fortunately, dramatic progress has been made in recent years, and in a section on X-ray detectors, three types of area pixel detectors, one of them commercially available, are discussed.

The production of intense coherent X-ray beams together with efficient area detectors stimulated the development of new imaging schemes, including X-ray holography and imaging of nonperiodic objects by diffraction of these coherent beams, which are discussed to great detail in two chapters in the subsequent section. Because of the high quality of today's X-ray beams and detectors, fundamental concepts in quantum optics can now also be studied in the hard X-ray range of the electromagnetic spectrum. In a chapter on quantum and nonlinear optics with hard X-rays, examples are presented making extensive use of nuclear resonances in Mössbauer isotopes.

Understanding the interaction of intense X-ray beams with atoms is crucial for all experiments with free-electron lasers because of their extremely high peak brightness, and therefore a theoretical chapter on the subject opens the section on novel investigations of atoms, molecules, and clusters. Spectroscopy plays an important role for investigations of the electronic structure of molecules, and a comprehensive overview of molecular soft X-ray emission spectroscopy, including resonant inelastic X-ray scattering (RIXS), is given in the second chapter of this section. In the following contribution, studies of molecular physics and gas-phase chemistry with free-electron lasers are described with an emphasis on the use of coincidence techniques best performed at facilities with high repetition rate. The last chapter in this section provides an overview of recent studies on clusters and nanoparticles using both soft and hard X-ray free-electron lasers.

Applications of synchrotron radiation in biology have been a highlight in X-ray science. In the next section of the book, chapters on biological soft X-ray tomography and on synchrotron small-angle X-ray scattering on biological molecules in solution and a more general overview nicely confirm this observation.

The last section of the book is devoted to applications in materials and condensed matter science, areas of research where X-rays have made outstanding contributions since their discovery in 1895. The first chapter describes the state of the art of angle-resolved photoemission, probably the most important spectroscopy tool in condensed matter physics. This chapter is followed by an overview of the application of micro- and nanobeams for materials science. Due to their polarization, synchrotron radiation and FEL beams couple very nicely to the magnetic properties of matter, which is used both in spectroscopy and scattering experiments. In a contribution on the X-ray view of ultrafast magnetism, results are described which provide insights into the switching of the magnetic moments which is important for improving data storage media. One interesting feature of modern storage rings is the fact that they provide high-brightness beams up to energies of 100 keV or more allowing for studies of buried interfaces and true bulk properties. As an example, the next contribution of this section describes a number of examples of high-energy X-ray scattering and imaging applications. Going from hard to soft matter, the next contribution describes in great detail synchrotron X-ray scattering from liquid surfaces and interfaces followed by a chapter on structural dynamics of materials probed by X-ray photon correlation spectroscopy. The investigation of phonons in matter is a domain of neutron scattering because of the excellent match of their energy with the energy of collective excitations in solids. However, due to the enormous progress in the brightness with synchrotron radiation sources and clever instrumentation, meV energy resolution at hard X-ray spectrometers can be achieved today. In addition, there are no kinematical limitations for studying scattering at high momentum transfer with X-rays. This section contains two chapters on high-resolution inelastic X-ray scattering, one describing spectrometers and samples with emphasis on superconductors and the other one dealing with scattering theory. A chapter reviewing nuclear resonance scattering with emphasis on studies of matter under extreme conditions and magnetic properties follows. The last contribution in the first issue of the Springer Reference on Synchrotron Radiation and Free-Electron Lasers is on high-resolution resonant inelastic X-ray scattering (RIXS) from solids in the soft X-ray range. The author’s main goal is to provide physical insight into the RIXS process before getting lost in the details of this complicated technique and to demonstrate its power by showing recent results on the dynamics of high-T_c superconductors including the dispersion of magnons and even bi-magnons.

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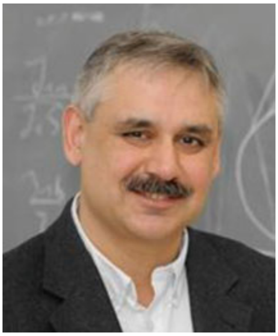
Eberhard Jaeschke studied Physics at the universities of Erlangen and Princeton. After his Ph.D. in Nuclear Physics, he moved to the Max-Planck-Institut für Kernphysik, Heidelberg, where his interests turned more and more to the physics of accelerators and their development. At Heidelberg University, he taught experimental physics, got his habilitation, and was promoted to professor (apl). The Heidelberg-TSR – the first heavy ion cooler ring with electron and laser cooling, which he managed as project leader – was a worldwide recognized success. From Heidelberg, Eberhard Jaeschke moved to Berlin, becoming member of the board of directors of the Berliner-Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY), and received a call for a full professorship at the Humboldt Universität. He was project director of the construction of BESSY II, the first German third-generation synchrotron light source. His marvelous team managed to build BESSY II in time and on budget and turned after this success to the design of modern light sources, the free-electron lasers (FELs).

Research stays over the years were at Los Alamos, Stony Brook, Tokyo, Chalk River, and at the Budker Institute of Nuclear Physics, Novosibirsk.

Eberhard Jaeschke retired from BESSY after 18 years on the board and is now professor emeritus. In 2010, he was awarded the Officer's Cross of the Order of Merit of the Federal Republic of Germany.



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Shaukat Khan studied Physics at Heidelberg University and received his doctor's degree in 1987 with work in nuclear spectroscopy at the Max Planck Institute for Nuclear Physics. While working as a postdoc on a silicon vertex detector for the ARGUS experiment at DESY/Hamburg, he became more and more interested in accelerator physics. Consequently, he joined the BESSY II project in Berlin in 1993 where his research interests included collective beam instabilities and the generation of ultrashort X-ray pulses. After receiving his lecturer qualification (habilitation) from the Humboldt University of Berlin, he became W2 professor at Hamburg University in 2006 and full professor at TU Dortmund University in 2008. In addition to holding a chair in accelerator physics, he is director at the university-based synchrotron radiation facility DELTA at which his working group develops laser-seeding techniques to produce ultrashort radiation pulses.

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Jochen Schneider studied Physics at the University of Hamburg and did his Ph.D. under the guidance of H. Maier-Leibnitz at the Institute Max von Laue-Paul Langevin in Grenoble, France. After working at the Hahn-Meitner Institute and the Technical University in Berlin, in December 1989 he moved to the Deutsches Elektronen-Synchrotron (DESY) in Hamburg, Germany. His main interest is in structural phase transitions and electronic properties of solids, as well as synchrotron radiation instrumentation. He developed γ-ray diffractometry and pioneered the application of high-energy synchrotron radiation in condensed matter research. In 1993 he became head of the synchrotron radiation laboratory HASYLAB at DESY; from 2000 to 2007 he was Photon Science Research Director. In his tenure, he initiated DESY's third-generation synchrotron radiation facility PETRA III, the free-electron lasers FLASH and European XFEL, and the Center for Free-Electron Laser Science (CFEL). After 2 years at SLAC National Accelerator Laboratory at Stanford in charge of the experimental facilities division of LCLS (the Linac Coherent Light Source), he is now a fellow of CFEL and scientific advisor to the DESY Directorate.

In 1981 Jochen Schneider received the Viktor-Moritz-Goldschmidt Award of the German Mineralogical Society, in 2001 the European Crystallography Prize, and in 2008 the Officer's Cross of the Order of Merit of the Federal Republic of Germany.

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Jerome Hastings studied Applied Physics at Cornell University and did his Ph.D. under the guidance of B. W. Batterman. After working at the National Synchrotron Light Source for nearly 25 years, in October 2001 he moved to the SLAC National Accelerator Laboratory in Menlo Park, CA, USA. His main interest is in methods and instrumentation for accelerator-based light sources. He developed the applications of ultrahigh-energy resolution methods applied to synchrotron-based Mössbauer spectroscopy and inelastic X-ray scattering. In addition he led the ultrashort pulse spontaneous radiation facility "Sub-Picosecond Pulse Source" at the SLAC National Accelerator Laboratory from 2001 to 2006. In his tenure at the National Synchrotron Light Source, the NSLS R&D effort developed many of the methods and instruments in common use today at third-generation synchrotron light sources. He is the science advisor for the LCLS and professor (research) in the Photon Science Faculty at the SLAC National Accelerator Laboratory. He is a fellow of the American Physical Society.

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