SYNCHROTRON RADIATION

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Summary

In recent decades synchrotron radiation (SR) has been harnessed as a potent probe of matter across the range from ultraviolet light to high-energy X-rays. Many experiments that are impossible with conventional X-ray and light sources are feasible with synchrotron radiation. The combination of properties that make it uniquely useful consists of the high brightness of the source, its energy tunability, and its high degree of polarization. After a brief historical introduction, the essential features of the synchrotron machine are explained and the optics of the beamlines that harness the

radiation are described. The most important synchrotron radiation-based techniques used to study a wide range of materials are then reviewed.

1. Introduction—Historical Perspective

With the benefit of hindsight the prediction of the phenomenon which we now call *synchrotron radiation* can be traced back to a number of scientific papers on electromagnetic waves which appeared around 1900, in which the radiation from an electron particle that was moving with a speed approaching the speed of light was considered. Notably Lienard working in Paris, France, in 1898 and then Schott 10 years later at Cambridge, then Aberystwyth, in the UK, showed that the radiative loss was proportional to the fourth power of the particle's energy. Three decades later, interest in cosmic rays accelerated in the earth's magnetic field led Pomeranchuk in Leningrad, Russia, to conclude that the electron energies at which the losses would be significant were astronomically high—much higher than we now know them actually to be. The generally agreed year of birth of synchrotron radiation is 1947 when scientists at General Electric's research laboratory in the USA observed visible light emitted tangentially from a new type of accelerator called a synchrotron. Then, as now, most particle accelerators were "rings" so that the particle can be made to circulate many times before it attains its maximum energy. The obvious method to ensure a circular trajectory is to apply a magnetic field perpendicular to the orbital plane. At non-relativistic velocities a magnetic induction B constrains a particle of mass m, charge e and energy E, to move in a circular path or radius r where $Bev = E/r$, but the radius r will increase if the electron is made more energetic by the application of electrostatic or radiofrequency electromagnetic fields. At highly relativistic energies $v \approx c$, where c is the speed of light in vacuum and

$$E = \frac{m_o c^2}{\sqrt{1 - \frac{v^2}{c^2}}} .$$

Thus the radius of the orbit may be written:

$$r = \frac{E}{Bec}$$

The name "synchrotron" derives from the synchronization between the value of the magnetic field and the electron energy that allows the charged particle to maintain a fixed orbit as its energy rises on successive cycles. The 1947 GE machine, which accelerated electrons up to a maximum energy of 70MeV, was table-top size and produced visible light whose mean wavelength could be seen to decrease with increasing particle energy.

At first the synchrotron radiation was viewed as an unfortunate energy-loss mechanism by the designers of high energy particle accelerators. Twenty years later, atomic and condensed matter scientists began to query whether these emissions could be used, and this led to the parasitic use of synchrotron radiation at accelerator centers, with all the attendant conflicts of interest between the particle and radiation scientists. The *first generation* of synchrotrons, exploited parasitically as light sources, dates from around 1970, with a *second generation* of machines, which were designed explicitly for SR research not only in the visible and ultraviolet spectral region but also in the x-ray regime, following on within a decade. They made possible crystallography as well as atomic and surface spectroscopy. This transition was necessarily accompanied by higher accelerator energies and also by the insertion into the ring of magnetic devices tailor-made to concentrate the photon output in particular spectral ranges. The current *third generation* of machines, which arrived in the last decade of the twentieth century, carry this process to its logical conclusion by having these "insertion devices" as their prime radiation sources, largely ignoring the simple bending magnets that ensure that the charged particles continue to orbit around the ring. The orbiting charged particles are stored in these machines with the radiative losses replaced in radiofrequency cavities. They are properly referred to as *storage rings*. At each stage of development the increases in the energy of the accelerated particle meant that the radius of the ring increased, since the maximum values of B available from permanent magnets remain approximately constant. At present there are three "large" storage machines establishments worldwide: ESRF at Grenoble, France, operating at 6 GeV; APS at Argonne, USA, operating at 7 GeV and SPRING-8 at Himeji, Japan, operating at 8 GeV. These "rings" are housed in buildings with circumferences of the order of 1 km. Other current storage ring developments are planned to operate at lower energies (2–4 GeV) and hence lower overall cost but possibly better, that is, lower, emittance (see Section 2.2).

Development beyond the brilliance limits of the storage rings will utilize linear devices that provide stimulated amplification of coherent radiation; the so-called *free electron lasers* will become the next (*fourth generation*) of light sources. The increase in the brilliance of x-ray sources from the early Roentgen tube is sketched in Figure 1, where the quantity plotted logarithmically is the brilliance of the x-ray source. Since the development of SR sources, the gain in both brightness and brilliance (see Glossary definitions) have been at the rate of a factor of ~1000 every decade. This progress with storage rings cannot continue unabated since there is a natural upper limit of ~10^{23} to the brilliance, which is imposed by diffraction effects. Machine designers have proved that storage rings can be made to operate close to their theoretical limits. Beyond that, free electron lasers will provide higher performance figures, but the power loading on the x-ray optics and the samples will change the nature of the experiments that can be done in favor of dynamic "pump and probe" type investigations.

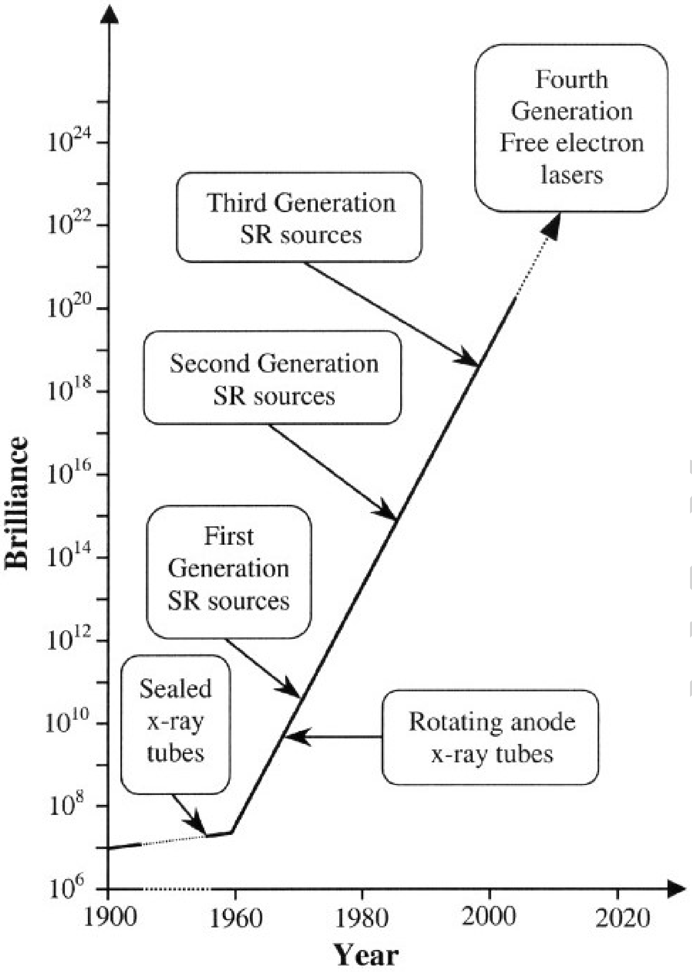

Figure 1. Sketch of the increase in x-ray source brilliance (see Glossary definition) from sealed and rotating anode x-ray tubes, through the successive generations of SR sources

(See *Electromagnetic Waves*, *Cosmic Rays*, *Synchrotron*, *Radiative Losses*, and *Coherent Radiation*.)

2. The Storage Ring

2.1. Elements of the Machine

Current machines are storage rings in which the charged particles are accelerated to their final energy, before being “stored” in the ring. For example, a linear accelerator (LINAC) is used to bring the electrons to, say, 5% of the operational energy, and then a booster synchrotron accelerates them up to their final energy. The stored charged particle is usually an electron, but several synchrotrons have used positrons, because positively charged particles are scattered less by residual ions in the vacuum of the ring. The production of positrons from electrons usually occurs by conversion of electrons in bombardment of a heavy metal target after the LINAC stage. In the rest of this article, the use of electrons rather than positrons will be assumed.

Electrons accelerated to full energy in the booster ring lose energy in the storage ring by the radiative process, namely the emission of synchrotron radiation, and by collision with residual gas molecules in the ultrahigh vacuum of the ring. The radiative energy losses can be made good by radiofrequency cavities, but the scattering of the beam by residual ions is irredeemable and leads to a slow decay and limits lifetimes. Current third-generation machines have lifetimes of the order of 10–50 hours which means that refills, which take 10–30 minutes, are needed just two or three times per day. Alternatively the gradual decay of the beam can be avoided by continuous “topping-up” from the booster. The dipole magnets, with a vertical field, provide the centripetal acceleration that maintains the closed orbit of the horizontal ring as well as producing synchrotron radiation. In practice off-axis electrons need to be restored to this central path by multipole (quadrupole; sextupole; octupole etc.) focussing magnets which are characterized by having zero field at the orbital position. The combination of magnet types that characterizes a synchrotron is called the magnet lattice, and the building block from which it is formed is called the magnetic cell. The number of cells required to close the orbit, that is, bend the beam through 360° ≙, is clearly dependent upon the strength of the dipole (bending) magnet field and the beam energy. The horizontal emittance ε_x of the synchrotron radiation depends strongly upon the particle energy, E, and the number of cells N_C, viz:

$$\varepsilon_x = \frac{E^2}{{N_C}^3} ,$$

which illustrates the sensitivity of the performance to design parameters. As shown earlier, the radius of the orbit, r, is also related to the particle energy, E, by $r = \dfrac{E}{Bec}$ This relationship largely fixes the size of the machine because of the limited magnetic field (~1 Tesla) that can be applied by permanent magnets sitting outside a vacuum vessel in which the beam circulates. The minimum magnet pole gap becomes a vital parameter unless superconducting magnets are used, which increases expense and complexity. Recently the siting of magnets in vacuum, thereby increasing the field strength, has been demonstrated to produce increases in flux, albeit at the expense of beam lifetime.

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Biographical Sketch

Malcolm Cooper was born in 1944 and educated at Leek High School and Clare College, Cambridge in the UK. He began his research work in the Cavendish Laboratory in 1964. In 1970 he moved to the University of Warwick where he is now a Professor in the Department of Physics. He has published over 150 research papers on the study of electron density distributions using Compton scattering techniques, latterly concentrating on the study of ferromagnetic materials by synchrotron radiation-based scattering and diffraction methods and has worked at most current synchrotron facilities. From 1997 to 2001 he chaired the Users' Organisation at the European Synchrotron Radiation Facility in Grenoble where he co-directs the UK-funded x-ray diffraction beamline. He is also currently the President of the International Radiation Physics Society.