Radiation sources: X-ray sources

A Pifferi, CNR—Institute of Crystallography, Rome, Italy

This is an update of A. Pifferi, X-Ray Sources, Editor(s): Franco Bassani, Gerald L. Liedl, Peter Wyder, Encyclopedia of Condensed Matter Physics, Elsevier, 2005, pp. 323–329, ISBN 9780123694010, https://doi.org/10.1016/B0-12-369401-9/00631-8.

Abstract

Since their discovery in 1895, X-rays have become a vital tool to determine the chemical and atomic structure of materials. It is currently used in many fields, including biological systems and human beings. X-ray technology has tremendously evolved from the first commercial x-ray tube built by Carl Heinrich Florenz Müller in 1896 to the modern synchrotron sources, allowing increasingly precise and sophisticated analyses in hard and soft matter.
In this chapter, after brief notes on cosmic ray sources, the devices capable of producing X-rays from vacuum tubes up to modern particle accelerators for the production of Synchrotron Radiation (SR) and Free Electron Lasers (FEL) are described.

Key points

- **Astrophysics** is a science that employs the methods and principles of physics and chemistry in the study of astronomical objects and phenomena
- **Atomic particle** All matter consists of atoms that contain a nucleus and orbiting electrons
- **Brehmsstrahlung** braking radiation; refers to any radiation produced by deceleration of a particle
- **Bending Magnet** Device used to bend the electron beam produced by an accelerator tube
- **CNT** Carbon Nano Tube
- **Laser Plasma** is a product of the very complicated process of laser-matter interaction
- **Synchrotron** is a particular type of cyclic particle accelerator
- **Undulator** is a device similar to a wiggler except that the B-field strength is more limited
- **Wiggler** is a series of magnets designed to periodically laterally deflect ('wiggle') a beam of charged particles
- **XFEL** Free Electron Laser sources that produce radiation with brightness several orders of magnitude higher then undulators on third-generation rings
- **X-ray** form of ionizing radiation
- **XRF** X-Ray Fluorescence is an analysis technique that can be applied to most inorganic materials

Introduction

X-rays are forms of ionizing radiations, i.e., they have enough energy to ionize atoms and molecules in matter, including the biological one represented by cells and tissues. They are electromagnetic radiations having a wavelength (λ) between 10 and 0.01 nm, frequency from about 3×10^{16} to 3×10^{19} Hz and having energy between 0.1 and 100 KeV.

"X-rays" was the name given by W. C. Roentgen to the highly penetrating rays that are produced when high-energy electrons strike a metal target. On November 8, 1895, he noted for the first time this phenomenon and on December 28, 1895, Roentgen astonished the scientific world with his preliminary report "Ueber eine neue Art von Strahlen" (Roengten, 1895) given to the president of the Wurzburg Physical-Medical Society (along with experimental radiographs and by the X-ray image of his wife's hand). A few weeks later C.H.F. Muller was able to construct in his factory in Hamburg the first commercial X-ray tube for one of local hospitals. This was a milestone of what was become a major technical industry. Röntgen received the Nobel Prize in Physics in 1901 for this discovery. X-ray technology is one of the most important inventions of the nineteenth century. It plays a major role in our daily life. X-rays are nowadays one of the most powerful tools to investigate hard and soft matter.

There are numerous applications of X-rays in the various fields of science and medicine. In addition to radiography, in the medical field, applications for Computed Axial Tomography (ACT), Micro tomography are known. In biology and chemistry, X-rays are used for structural determination of both inorganic and biological molecules by X-ray diffraction from crystals (Giacovazzo, 2002). Baggage inspection is based on X-ray imaging in checkpoints of airports or sensitive areas, to control the structural integrity of aircrafts and transports or more generally, to inspect the insights of materials subjected to mechanical/thermal stress. In the food industry, X-ray are used to check for the presence of extraneous objects inside the packaging. In the field of Cultural Heritage to analyze paintings, archaeological finds, or to carry out elemental analyses in pigments or in metals using Fluorescence X (XRF). Of course, different types of radiation sources have been studied and developed for each application.

In nature, as it turned out later, there are sources of X-rays generated by cosmic processes or nuclear particles decay phenomena.

Natural sources (astronomy)

X-ray source, in astronomy, are cosmic objects that emit radiation at X-ray wavelength (Britannica, 2018). Since the Earth's atmosphere absorbs X-rays from space, detectors and telescopes capable of measuring the weak emissions generated by celestial bodies have been launched into space (high above Earth's atmosphere) The sun was the first celestial object for which radiations in the range of X-rays wavelengths were measured (1949). The radiations coming from the sun are substantially weak and it is notable only because its proximity to the Earth. Only 30 years later with the launch of the HEAO 2 satellite better known as the Einstein Observatory (Giacconi et al., 1979), more than 150 stars emitting X radiation were observed.

In Astronomy, X-rays come from material that has been heated to extreme temperatures by a small number of physical processes:

(1) Accretion: material falls within the gravitational potential of a celestial body, potential energy is converted into kinetic energy, and via different processes (collisions, friction) into heat, and the heated material cools then by emitting X-rays. Common environments where accretion occurs are binary stars, in particular those containing "stellar remnants," i.e., white dwarfs (Pravdo et al., 1986), neutron stars (Morton, 1964), and black holes (Wilkins et al., 2021). Because of their extreme densities, material is accelerated to 1000s of km/s (white dwarfs) to highly relativistic velocities (neutron stars, black holes), which then facilitates heating material to very high temperatures. However, also young (single) stars that are still in the process of formation accrete from a proto-stellar disc, and the most luminous X-ray sources are super-massive black holes (millions to billions of solar masses) in the centers of most (maybe all) galaxies, accreting interstellar dust/gas.

    In terms of heating processes, there are two main branches:

    - Shock-heating of material that is abruptly decelerated, e.g. in the case that it hits the stellar "surface" (=atmosphere), which is the case if the accreting star has a sufficiently strong magnetic field (young some white dwarfs, most neutron stars). Material cools via thermal bremsstrahlung.
    - In the case of no/weak magnetic fields of the accreting object, an accretion disk (flat structure) forms, material drifts inwards, angular momentum is transported outwards, and gravitational energy is gradually converted into heat via friction. Temperatures in the inner discs around white dwarfs, neutron stars, and black holes reach temperatures where they emit X-rays (again, material simply cools, and emits thermal bremsstrahlung).

    So the process of generating the X-rays in these systems is fairly general, and does not depend too much on the detailed properties of the accreting object.

(2) High-energy processes within the outer layers of stars, generally called "stellar activity," such as e.g. in the sunspots. These are related to magnetic phenomena (twisted field lines, magnetic reconnection). As such, the Sun is an X-ray source—and some other stars are much more active and X-ray luminous.

Conventional sources

X-ray tube

Whenever a charged particle is accelerated or decelerated, it emits energy in the form of photons. This process takes place within an X-ray tube to create X-rays. At one end of the tube is the source of electrons or the cathode and at the other end of the tube is the metal target, or anode. To produce X-rays, electrons are accelerated from the cathode to the anode with a high voltage. When the electrons hit the anode, they are quickly stopped. This rapid change in speed causes the emission of X-ray photons. These X-rays are commonly called brehmsstrahlung or "braking radiation."

Bremsstrahlung is the German word for slowing down or braking. Bremsstrahlung is an electromagnetic radiation produced by the deceleration of a charged particle, deflected by another charged particle, typically an electron by the atomic nucleus. Assuming

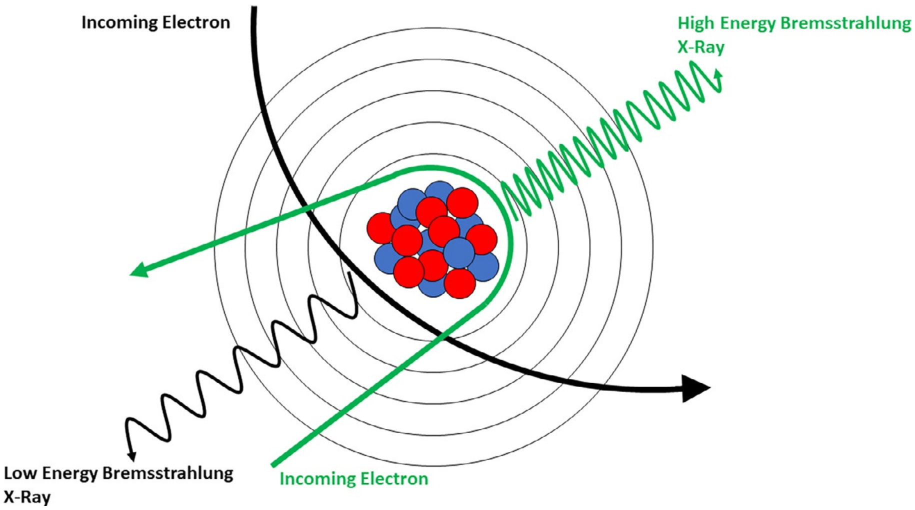

Fig. 1 Radiation produced by an electron passing through an atom and being deflected by the nucleus.

that there are charged particles in a piece of matter and that a high-speed electron passes close to it, the trajectory of the latter will be deflected due to the electric field around the atomic nucleus, as shown in the image (Fig. 1).

The moving particle, when deflected, loses kinetic energy and, to satisfy the energy conservation principle, emits radiation in the form of a photon; bremsstrahlung radiation is characterized by a continuous distribution of radiation that becomes more intense (and moves towards higher frequencies) with the increase in the energy of the bombarding electrons (braked particles).

An electron that completely avoids the orbital electrons on passing through an atom of the target may travel sufficiently close to the nucleus of the atom to come under its influence. Since the electron is negatively charged and the nucleus is positively charged, there is an electrostatic force of attraction between them. As the electron approaches the nucleus, it is influenced by a nuclear force much stronger than the electrostatic attraction. As it passes by the nucleus, it is slowed down and deviated in its course, leaving with reduced kinetic energy in a different direction. This loss in kinetic energy reappears as an X-ray photon.

If all the energy carried by an electron is transformed into radiation, the energy of an X-ray photon is

$$E_{max} = h\nu_{max} = eV$$

Where h is the Plank's constant, ν_{max} the photon frequency. The indication max indicates that this is the maximum possible energy, e is the charge of the electron and V the acceleration potential. If the frequency is substituted with the wavelength, the above expression becomes

$$h\nu_{max} = hc/\lambda_{min} = eV \quad \text{and} \quad \lambda_{min} = hc/eV = 12398/V$$

The energy contained in each bremsstrahlung photon emitted from an X-ray tube extends from that associated with the peak electron energy all the way down to zero. In other words, when an X-ray tube is operated at 70 kVp, bremsstrahlung photons with energies ranging from 0 to 70 keV are emitted, creating a typical continuous X-ray emission spectrum. Since total conversion of the electron energy into radiation is not a highly probable event, the radiation of the highest intensity is obtained at a longer wavelength compared to λ_{min} (1.5 times). Fig. 2 shows some X-ray continuous spectra as a function of the accelerating voltage.

If the bombarding electrons have sufficient energy, they can knock an electron out of an inner shell of the target metal atoms. Then electrons from higher states drop down to fill the vacancy, emitting X-ray photons with precise energies determined by the electron energy levels. These X-rays are called characteristic X-rays. In summary, transitions of orbital electrons from outer to inner shells produce characteristic X-rays. Since the electron binding energy for every element is different, the characteristic X-rays produced by the various elements are also different. This type of X-radiation is called characteristic radiation because it is characteristic of the target element. The effective energy characteristic X-rays increases with increasing atomic number of the target element. The characteristic lines of this type of spectrum are called K, L and M and correspond to the transition from higher energy orbital to the K,L,M orbital. When the two orbital involved in the transition are adjacent then the line is called α, if they are separated by another shell the line is called β (Fig. 3).

For example, K electrons for tungsten anode have binding energies of 69.5 keV, and L electrons are bound by 12.1 keV. Therefore, the characteristic X-ray emitted has energy

$$69.5 - 12.1 = 57.4 \text{ keV}$$

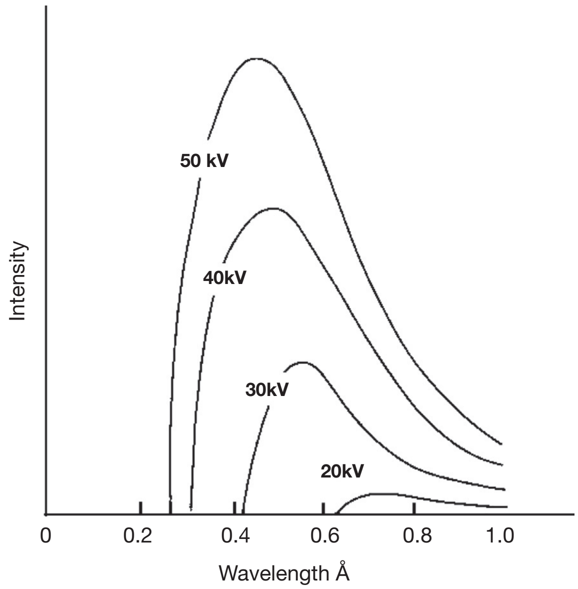

Fig. 2 X-Ray radiation spectra as a function of accelerating voltage.

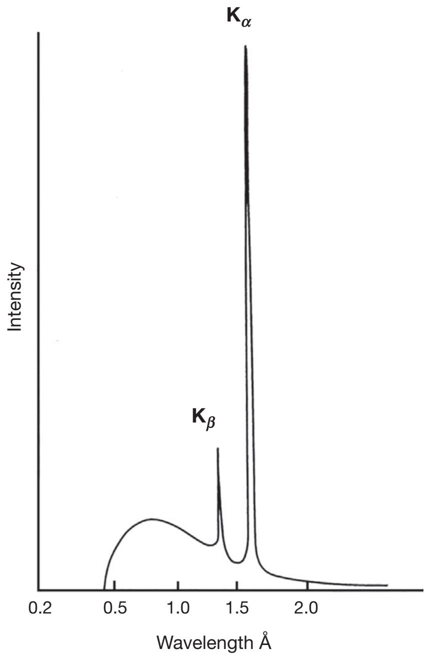

Fig. 3 Characteristic lines K_α and K_β of Cu spectra superimposed on the brehmsstrahlung.

Sealed tube and rotating anode sources

The X-ray tube is a large diode valve, which is designed to produce fast moving electrons and then cause the electrons to decelerate rapidly in a vacuum environment. A conventional generator consists of a high-voltage power supply electronically controlled applied between the anode and the cathode. In Fig. 4 the sketch of a sealed tube is showed.

It consists of a cathode with a filament that emits the electrons that are accelerated under vacuum by the high voltage. The electrons hit the anode and produce the characteristic X-ray spectrum relative to the metal of the anode. The high vacuum is necessary because the presence of gas molecule would decrease the efficiency of the tube. Normally this type of sources is highly inefficient because only 0.1% of power used is transformed into X-ray, the rest is dissipated as heat. In the rotating anode the anode has a cylindrical shape and to increase the efficiency of the X-ray beam the anode is continuously rotated. Thus, the electron beam

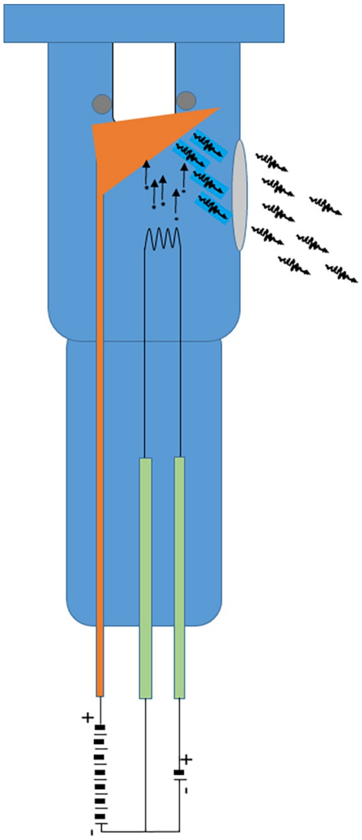

Fig. 4 Sketch of a sealed X-ray tube.

hits the metal of the anode in different positions permitting a better dissipation of heat. The increasing of the intensity of the beam may be quite an order of magnitude in respect to a sealed tube.

The intensity of a K line can be calculated using the equation:

$$I_K = Bi(V - V_K)^{1.5}$$

Where B is a constant, i the electrical current, and V_K the excitation potential of the K series. If the accelerating potential $V = 4V_K$ is applied the $K\alpha$ line is 90 times more intense then the white radiation of the equivalent wavelength (I_W). In this condition the ratio I_K/I_W is a maximum.

X-ray tube based on carbon nanotube field emitters

Over the last few decades, the technology for manufacturing X-ray sources has not substantially changed. Different types of generators have been developed according to the applications for which X-rays are used, i.e., in high definition medical diagnostics, safety inspection or high throughput industrial control processes (Parmee et al., 2015). The thermionic sources are limited due to the slow temporal response and the size and spatial amplitude of diffusion. For these reasons, new types of field emission X-ray sources have been studied.

In the tubes with Thermionic Emission (TE) the electrons are produced from a metallic filament, often consisting of Tungsten, which when crossed by an electric current heat it to a temperature above 1000 °C. Since the emission is strictly dependent on the temperature of the filament, as the temperature of the emitter increases the electrons able to overcome the surface barrier increase. In such tubes the filament current is controlled analogically. One of the disadvantages of this type of technology is the large production of heat that must generally be disposed of by cooling with the circulation of water or coolants. A second limitation consist in the slowness of the response when it is necessary to rapidly vary the intensity of the electron beam to increase or decrease the intensity of the X-ray beam. This slowness is due to the inertia in the heating or cooling of the filament.

Field Emissions (FE) offer several significant benefits. FE sources are often physically more compact than TE systems. The emission process occurs at room temperature and therefore does not require a heat sink. FE is a tunneling process and consequently provides almost instantaneous emission. The rise times are of the order of the microseconds as opposed to the TE that are of the order of milliseconds.

CNT-based emitters have several advantages over thermionic electron sources (Heo et al., 2012). The advantages are in the fact of having little heat generation compared to a thermionic tube, an important characteristic for creating small sources. They are simple to make and easily electronically controlled to generate pulses even of high frequency. Finally, they allow generating high current densities for electron and X-ray microscopy devices.

Synchrotron sources

Synchrotron radiation (SR) is emitted when charged particles moving with relativistic speeds are forced to follow curved trajectories in magnetic fields. The first visual observation of SR was in 1948 from the General Electric synchrotron in the USA during investigations into the design and construction of accelerators suitable for the production of very high-energy electrons. Over the next 50 years, an explosive growth in the building of accelerators optimized for SR production has turned this interesting radiative energy into a valuable research tool (Winik, 1995).

Whenever charged particles undergo an acceleration they emit electromagnetic radiation. An electron oscillating at radio-frequencies in an antenna emits radio waves. When electrons are subjected to an acceleration perpendicular to their velocity, for example when they pass through a magnetic field, their direction is changed and they begin to travel in a circular path. Charged particles moving under the influence of an accelerating field emit electromagnetic radiation. The energy of this radiation is dependent on the velocity of the particle. The total instantaneous power P emitted by an electron moving on a circular orbit is

$$P = \frac{2e^2 cE^4}{3R^2 (m_0 c^2)^4} = \frac{2e^2 c\gamma^4}{3R^2} \tag{1}$$

where P is the energy emitted per unit time, e is the particle charge, c the speed of light, E the energy of the particle, m_0 its mass at rest and R the bending radius of the orbit. The emitted radiation has very different characteristics in dependence of the velocity v of the particle. If $v \ll c$ the emitted pattern is identical to the well-known dipole radiation field (Fig. 5a). When the speed increases to almost light velocity the whole power is compressed into a narrow cone in forward direction tangentially to the orbit (Fig. 5b). The radiation emitted is called synchrotron radiation. The quantity γ in eqn. 1, which is the ratio of the total energy to the rest energy of the particle, is of considerable importance since it is related to the opening angle $\Delta\Psi$ of the cone of radiation in the perpendicular plane of the orbit by:

$$\Delta\Psi \cong 1/\gamma$$

where $\Delta\Psi$ is expressed in radians.

A storage ring synchrotron consist of an arrangements of devices where charged particles travel at essentially the speed of light in evacuated pipes under the influence of magnets which are positioned around a closed orbit (Winik, 1995). Acceleration is achieved by the application of radio frequency electric fields at RF cavities along the circumference of the ring. The magnetic fields grow synchronously with the acceleration in order to keep the particles on the constant radius path. Such accelerators can be used with protons or electrons, and even with heavier positive ions. The particles travel in the closed loop for periods of several hours while synchrotron radiation spread out from all curved parts of the orbit.

In general, three kinds of magnets are used to make the necessary magnetic fields: bending magnets, wigglers and undulators.

Bending magnets

In bending magnets, a simple dipole structure is used to constrain the electrons in a curved path. The radiation emitted is extremely intense and extends over a broad wavelength range from the infrared through the visible and ultraviolet, and into the soft and hard

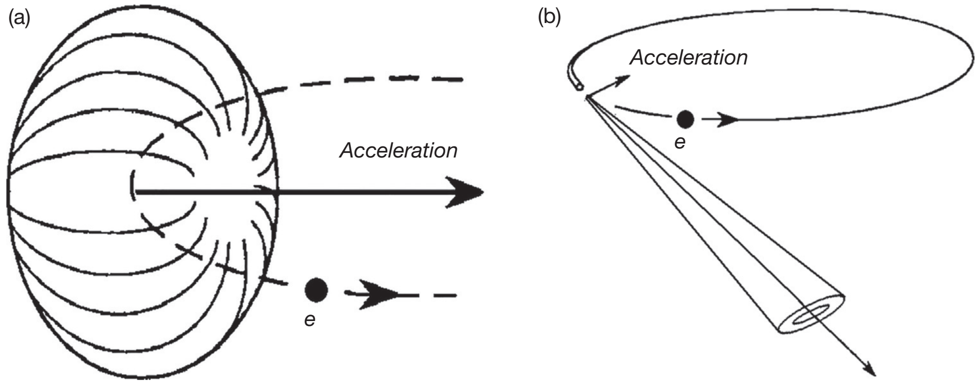

Fig. 5 Emission pattern of radiation from centripetally accelerated electrons: (a) non relativistic case $v \ll c$. (b) relativistic case $v \cong c$.

X-ray regions of the electromagnetic spectrum. A typical output curve for a bending magnet source has a smooth spectral distribution with a broad maximum near the so-called critical wavelength. This critical wavelength depends on the square of the energy of the electrons and the bending radius in the dipole. In practical units of angstroms, it can be calculated as:

$$\lambda c = 18.64/\left(B * E^2\right),$$

where B (the dipole field) is in Tesla and E (the ring energy) is in GeV. The critical wavelength (or energy) has the property that one-half of the power radiated is above this wavelength and one-half below.

Wigglers

High-field wiggler magnets are often used as sources in order to increase the flux at shorter wavelengths. We can best think of a wiggler as a sequence of bending magnets of alternating polarities which gives a 2 N enhancement in the flux, where N is the number of poles (Fig. 6). Each magnet bends the electron beam through an angle large compared with mc^2/E. The properties of wiggler SR are thus very similar to that of dipole radiation with a reduction in the critical wavelength because of the higher field. For superconducting wiggler magnets a value of 6 Tesla, as opposed to around 1.2 Tesla for conventional dipoles, would be typical. The characteristics of the synchrotron radiation from the wiggler are the same one as from the bending magnet, and so, the critical energy play a determinant role. To reach the same spectral range as from the bending magnets the magnetic flux density within the wigglers must be the same as within the bending magnets, if the magnetic field in the wiggler is higher than the ring bending magnet field, the wiggler spectrum extend to higher photon energy. The photon flux as well as the central intensity of the radiation emitted by the wiggler is the same as from the bending magnet but more intensive by a factor Np, where Np is the number of poles within the wiggler.

Undulators

An undulator magnet is similar to a wiggler, in that it is also a succession of alternating magnetic poles (Fig. 7a). However, in this case the angle of bend in each pole is of the order of mc^2/E, so that the small angular divergence due to the emission pattern of synchrotron radiation is not significantly increased. The radiation emitted at the various poles interferes coherently resulting in the emission of a pencil-shaped beam (Fig. 7b) peaked in narrow energy bands at the harmonics of the fundamental energy. For N poles, the beam's opening angle decrease by a factor $N^{1/2}$ and thus the intensity per solid angle increases as N^2.

Fig. 8 shows the performance in terms of brilliance of bending magnets, wigglers and undulators for a 6 GeV Energy synchrotron with a current in the ring of 100 mA.

Synchrotron radiation characteristically is highly polarized and continuous. Its intensity and frequency are directly related to the strength of the magnetic field and the energy of the charged particles affected by the field. Accordingly, the stronger the magnetic field and the higher the energy of the particles, the greater the intensity and frequency of the emitted radiation. The high intensity, broad spectral range and other properties such as collimation, polarization, pulsed-time structure, partial coherence, make synchrotron radiation a powerful tool for basic and applied studies in biology, chemistry, medicine, and physics, as well as in applications to technology such as X-ray lithography, micromechanics, materials characterization and analysis. Brilliance of

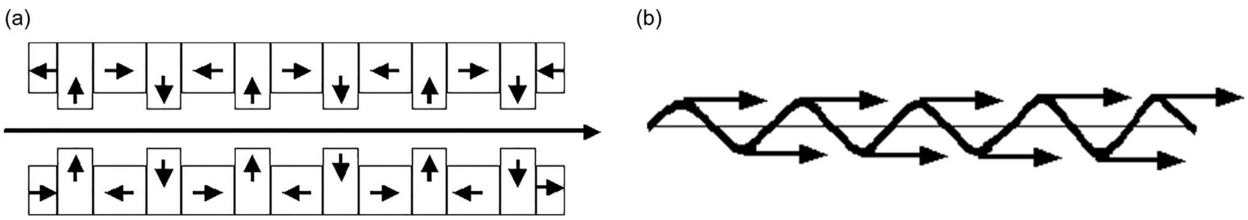

Fig. 6 (a) The arrangement of magnets within an wiggler. Horizontal arrows indicate permanent magnet vertical arrows indicate magnetic steel. (b) The trajectory of an electron beam within a wiggler. The arrows symbolize the emitted synchrotron radiation.

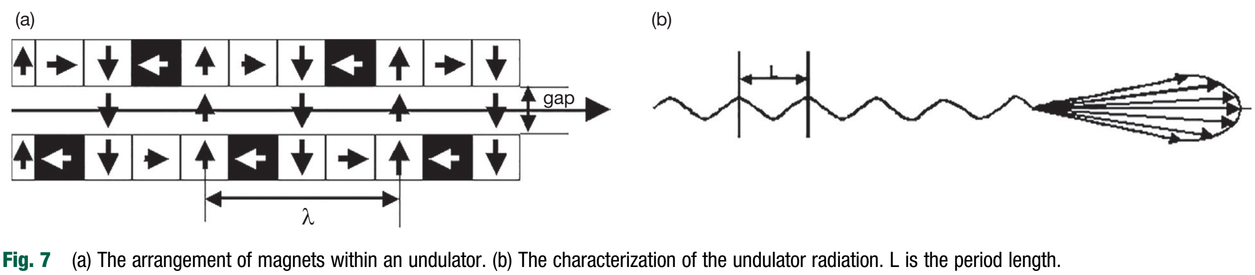

Fig. 7 (a) The arrangement of magnets within an undulator. (b) The characterization of the undulator radiation. L is the period length.

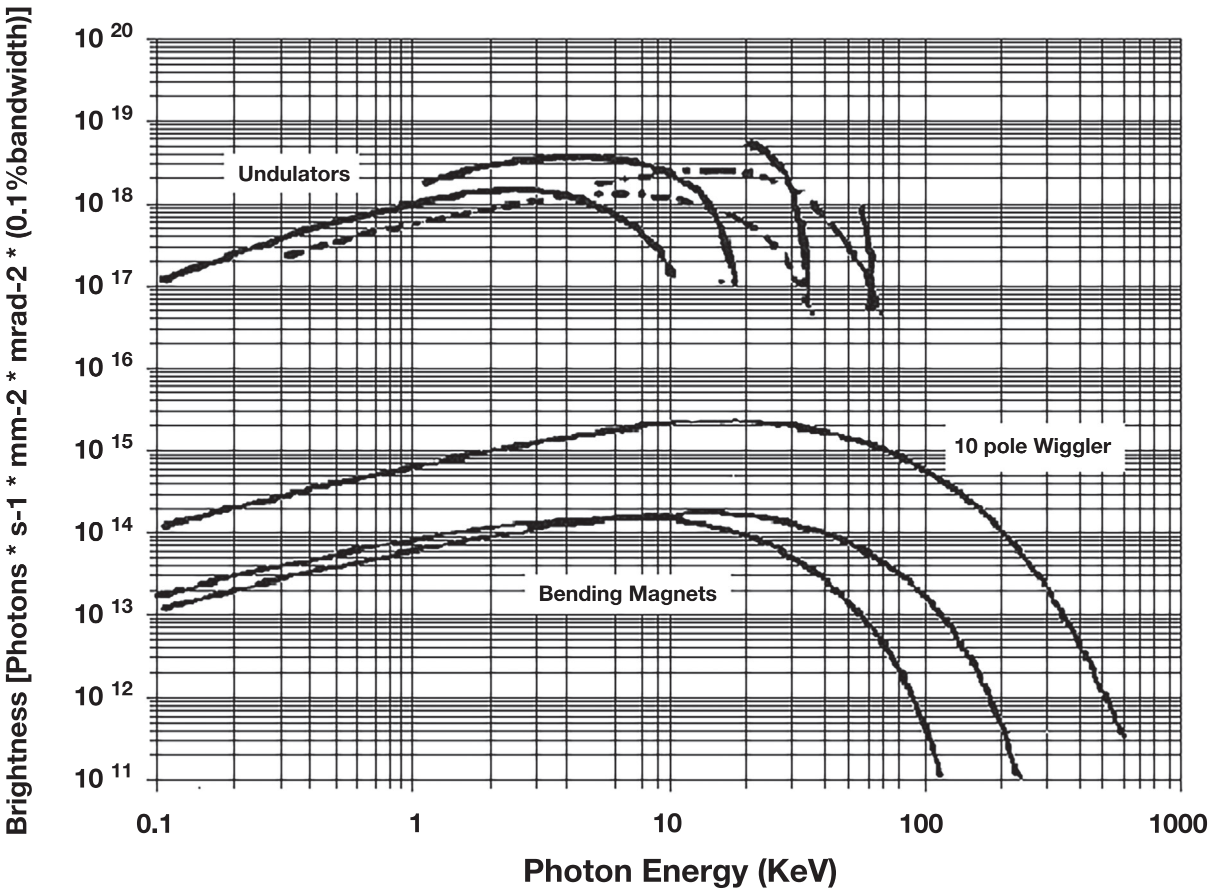

Fig. 8 Plot of Brilliance versus Photon Energy for a storage ring of 6 GeV Energy and 100 mA current.

synchrotron sources, up to $\sim 10^{10}$ larger than X-ray tube, mostly due to much smaller angular divergence. This is important because many experiments use small samples (e.g. protein crystals!) that can use only a tiny fraction of radiation emitted by tube. Much higher intensity make possible to observe very weak signals not observable with tube source, much tighter angular collimation is especially important for small samples, e.g. protein crystals, high pressure applications, etc. (Giacovazzo, 2002). By the use of special optical elements, such as monochromators, single energies can be selected among the continuous spectrum of Synchrotron Radiation; this energy tunability is of extremely importance especially for experiments driven near the absorption edge of specific elements.

Fourth generation light sources

The development of Fourth Generation Light Sources has been pointed out on Free Electron Lasers (FELs) (Pellegrini and Stöhr, 2003; Pant, 2015; Freund and Antonsen, 2018). Such sources produce radiation with brightness several orders of magnitude higher then undulators on third-generation rings. Graph in Fig. 9 shows the trend of the growth of the brilliance of X-ray sources starting from the beginning of the XX Century.

Radiation from a FEL has much in common with radiation from a conventional optical laser, such as high power, narrow bandwidth and diffraction limited beam propagation. One of the main differences between the two lasers is the gain medium: in a conventional laser the amplification comes from the stimulated emission of electrons bound to atoms, either in a crystal, liquid dye or a gas, whereas the amplification medium of the FEL are "free" (unbound) electrons. The free electrons are stripped from atoms in an electron gun and are then accelerated to relativistic velocities. While the electrons are propagating in an undulator the interaction with an electromagnetic radiation field leads to an exponential growth of the radiation emitted by the electrons. This amplification of radiation is initiated by an increasingly pronounced longitudinal density modulation of the electron bunch. The initial radiation field can be an external one, e.g. a seed laser, or an "internal" field, i.e., the spontaneous emission of the undulator. In the latter case it is called a SASE (Self Amplified Spontaneous Emission) FEL. Oscillating through the undulator, the electron bunch then interacts with its own electromagnetic field created via spontaneous emission. Depending on the relative phase between radiation and electron oscillation, electrons experience either a deceleration or acceleration: electrons that are in phase with the electromagnetic

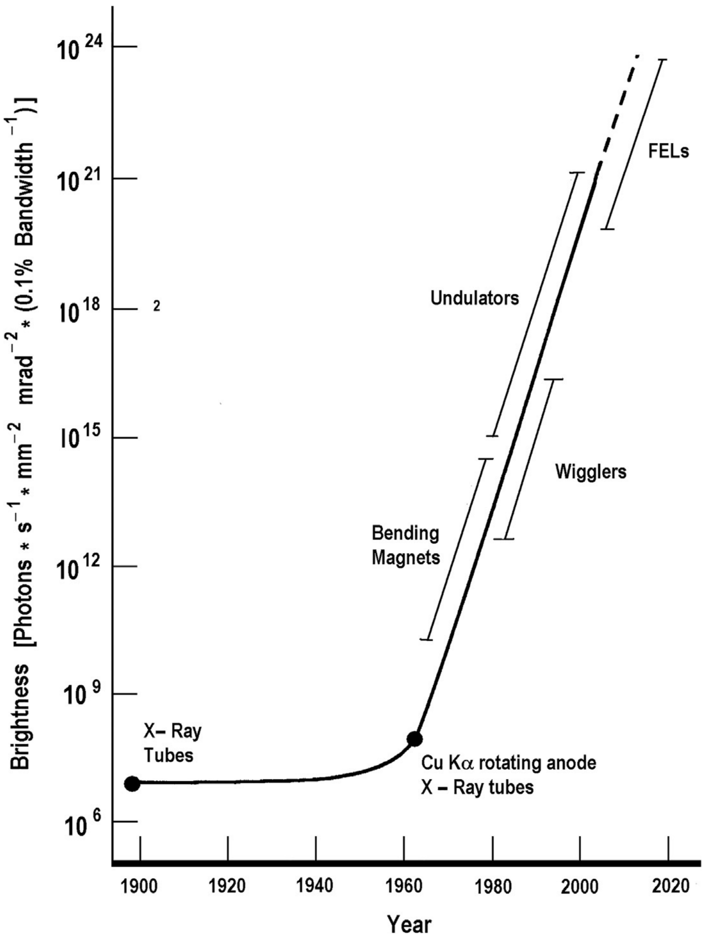

Fig. 9 Trend of the Brightness of X-ray sources plotted starting from the beginning of 1900.

wave are retarded while the ones with opposite phase gain energy. Through this interaction a longitudinal fine structure, the so-called micro bunching, is established which amplifies the electromagnetic field. The longitudinal distribution of electrons in the bunch is "cut" into equidistant slices with a separation corresponding to the wavelength λ_{ph} of the emitted radiation, which causes the modulation. More and more electrons begin to radiate in phase, which results in an increasingly coherent superposition of the radiation emitted from the micro-bunched electrons. The more intense the electromagnetic field gets, the more pronounced the longitudinal density modulation of the electron bunch and vice versa. The characteristics of FEL radiation are high power, short pulse length (pico to femtoseconds), narrow bandwidth, spatial coherence and wavelength tunability. Of particular importance are detectors capable of measuring such fast and intense signals (Knoll, 2012; Antonelli et al., 2013). Technology is constantly advancing in the construction of these devices.

Laser plasma X-ray sources

The concept for X-ray lasers goes back to the 1970s, when physicists realized that laser beams amplified with ions would have much higher energies than beams amplified using gases. Nuclear explosions were even envisioned as a power supply for these high-energy lasers. In X-ray lasers (Umstadter, 2015), a pulse of light strikes a target, stripping its atoms of electrons to form ions and pumping energy into the ions ("exciting" or "amplifying" them). As each excited ion decays from the higher energy state, it emits a photon. Many millions of these photons at the same wavelength, amplified in step, create the X-ray laser beam. Compact short-pulse high-power X-ray sources can be produced by focusing on a solid target ultra short laser pulses of low or moderate energy (from several to ten or a hundred millijouls) but of high intensity ($\geq 10^{15}$ Wcm^{-2}). For example, subpicosecond laser pulses can produce X-ray pulses of high power and short duration (in the picosecond range). With respect to hard and soft X-ray emission, such laboratory X-ray sources offer the following advantages over conventional X-ray sources such as synchrotrons: a greater compactness, an easier access, a lower cost, a shorter pulse length and a smaller source size.

Conclusions

The future of the research in the field of X-ray sources will be more and more bonded to the possibility to manipulate optically the radiation and to obtain a selective detection of the photons in order to perform ever more accurate spatial and temporal analysis. The use of these new methodologies of detection is already allowing to develop new X-ray sources and to study new physical phenomena until now inaccessible.

References

Antonelli M, et al. (2013) Fast synchrotron and FEL beam monitors based on single-crystal diamond detectors and InGaAs/InAlAs quantum well devices. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 730.
Britannica T (2018) Editors of encyclopaedia. In: *"X-ray Source." Encyclopedia Britannica, September 12*. https://www.britannica.com/science/X-ray-source.
Freund HP and Antonsen TM (2018) Principles of free-electron lasers. Cham: Springer. https://doi.org/10.1007/978-3-319-75106-1.
Giacconi, et al. (1979) The Einstein (HEAO 2) X-ray observatory. *The Astrophysical Journal* 2301: 540–550.
Giacovazzo C (ed.) (2002) *Fundamentals of Crystallography, IUCr*. New York, USA: Oxford University Press Inc.
Heo SH, et al. (2012) A vacuum-sealed miniature X-ray tube based on carbon nanotube field emitters. *Nanoscale Research Letters* 7(2): 258.
Knoll GF (2012) *Radiation Detection and Measurement*. New York, USA: John Wiley & Sons.
Morton DC (1964) Neutron stars as X-ray sources. *Nature* 201: 1308–1309.
Pant K (2015) Free electron lasers. In: *Laser Physics and Technology*, 151–164. https://doi.org/10.1007/978-81-322-2000-8_7.
Parmee RJ, et al. (2015) X-ray generation using carbon nanotubes. *Nano Convergence* 2(2015).
Pellegrini C and Stöhr J (2003) X-ray free-electron lasers—Principles, properties and applications. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 33–40.
Pravdo SH, Marshall FE, White NE, and Giommi P (1986) X-rays from the magnetic white dwarf PG 1658 + 441. *The Astrophysical Journal* 300: 819.
Roengten W (1895) *Ueber eine neue Art von Strahlen. Vorläufige Mitteilung. Aus den Sitzungsberichten der Würzburger Physik.-medic.* Gesellschaft Würzburg 137–147.
Umstadter DP (2015) All-laser-driven Thomson X-ray sources. *Contemporary Physics* 56(4): 417–431.
Wilkins DR, Gallo LC, Costantini E, Brandt WN, and Blandford RD (2021) Light bending and X-ray echoes from behind a supermassive black hole. *Nature* 595(7869): 657–660.
Winik H (1995) *Synchrotron Radiation Sources.* World Scientific. Winick Editor.