Chapter

Fundamental of Synchrotron Radiations

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Abstract

Synchrotron radiations are emerging as a real-time probing tool for the wide range of applied sciences. Synchrotron radiations have unique properties because of their high brilliance, collimations, broad energy spectrum, and coherence power that break the limits to characterize the material properties than previous laboratory-based tabletop sources. The third-generation synchrotron light sources are capable of producing 10^{12} times higher brilliance than laboratory-based sources using insertion devices. In this chapter, the fundamental aspects of synchrotron radiations and their generation process have been discussed. The effect of insertion devices and the double-crystal monochromator (DCM) toward the X-ray beam optics has been also discussed.

Keywords: synchrotron radiation sources, insertion devices, double-crystal monochromator, brilliance, X-ray optics

1. Introduction

The synchrotron is basically a cyclotron in which relativistic charged particles are forced to follow curved trajectories under applied magnetic fields, and due to such motion, they emit electromagnetic radiations (infrared to hard X-rays) known as synchrotron radiations [1, 2]. Synchrotron radiations were first observed in 1947 at General Electric particle accelerator, USA, but were considered a nuisance because they caused the loss in particle energy and treated as a particle physics problem [1]. In the 1960s, they were accepted as an exceptional property of light that overcame the shortcomings of X-ray tubes [1, 3]. The exponential growth in the use of synchrotron radiation began after realizing its importance in condensed matter physics. At present, synchrotron radiations are widely used for the structural analysis of the matter, from the surface of solids to protein molecules [4, 5].

A synchrotron is composed of five main components: electron source, booster ring, storage ring, RF (radio-frequency) supply, and beamlines. In general, electrons are generated by the thermionic emission from a hot filament (electron gun) which serves as a source [1–3]. The electrons are then accelerated by either microtron or linear accelerator (LINAC) to several hundred MeV of energy.

The electrons are then injected to a circular accelerator to boost its energy to approach main storage ring electron energy, called booster ring. Electrons are periodically transferred to storage rings from booster when storage ring current falls to $1–1/e \sim 70\%$ to maintain beam current [3].

The storage ring is the main component of a synchrotron, in which electrons travel in a closed path under the effect of magnetic field. The main magnetic components are a set of magnets: bending (dipole), quadruple and sextuple magnets, so-called magnet lattice. Bending magnets force the electrons to follow the closed path, and the beam is focused by quadruple magnets via compensating electronic coulomb repulsion. Sextuple magnets serve as a corrector for chromatic aberration governed from quadruple focusing [1–4].

In the storage ring, the electrons travel at relativistic (99.999%c) speed and kinetic energies of the order of GeV. The modern ring structure consists of a periodic arched section having bending magnets and straight sections composed of insertion devices that are used to produce intense synchrotron radiations, which are named as the “third-generation storage ring” [4] as shown in a **Figure 1**.

As the electrons are accelerated in a circular path, they radiate at frequencies in the visible, ultraviolet, and X-ray regions of the spectrum and lose their energy. A radio-frequency (RF) cavity supplies suitable amount of energy each time the electrons pass through it, to prevent the electron scattering from an inner wall of the storage ring [1–4].

The beamlines are working along the axes of insertion devised and tangential to bending magnet and the storage ring. The beamlines are designed for specific dedicated applications, i.e., X-ray imaging (tomography), X-ray absorption spectroscopy (X-ray absorption fine structure (XAFS), near-edge and extended-edge spectroscopy (XANES, EXAFS)), X-ray scattering (small- and wide-angle X-ray scattering) and X-ray fluorescence/emission spectroscopy (XRF).

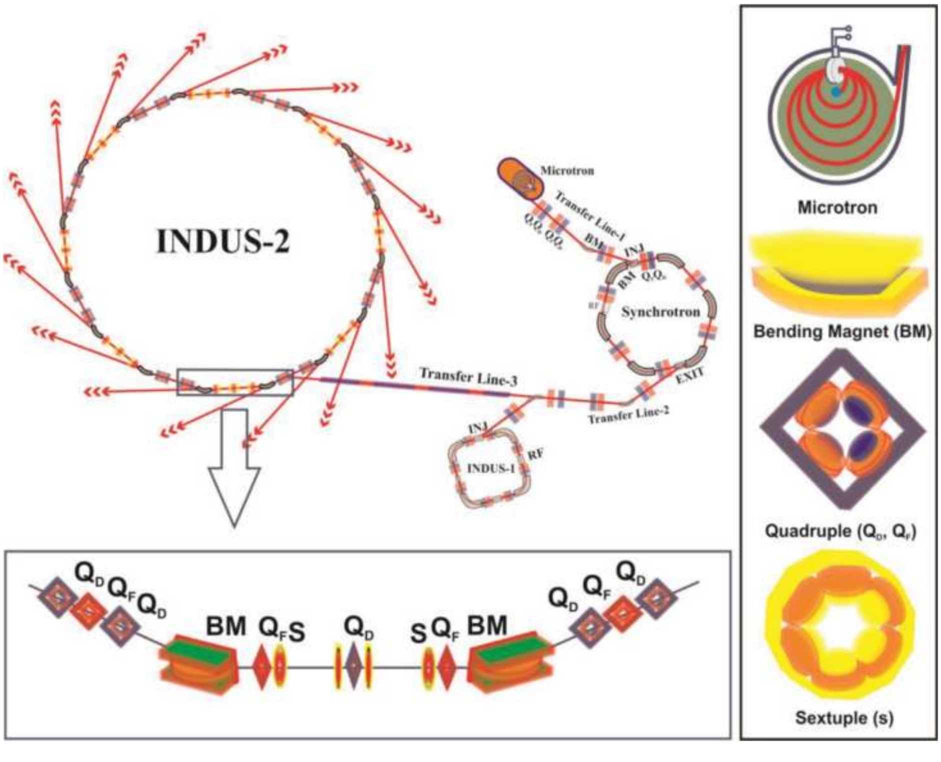

Figure 1.
Detailed outer structure of RRCAT—Indian third-generation synchrotron light source. Electrons are generated via microtron and transferred to the synchrotron for making an accelerated e^-*-beam. The energetic* e^-*-beam has been introduced to the Indus-1 and Indus-2 via transfer lines. The beam optics have been maintained by the periodic repetition of several magnetic components (quadruple focused (*Q_F*), quadruple defocused (*Q_D*), sextuple (S), and bending magnets (BM)) to force* e^- *beam to follow a circular path.*

2. Synchrotron radiation properties

Synchrotron radiations are highly polarized, are intense, and have the broad spectral range from infrared to hard X-ray region. These properties are tunable and can be understood by classical electrodynamic laws [1]. When a charged particle (electron) is moving in a circular path having energy much less than its ground state energy ($mc^2 = 0.51$ MeV), it behaves as weak dipole which radiates isotropically. In case of relativistic energy, the radiated energy folded in the forward direction makes a narrow cone with a solid angle $\psi \sim \gamma^{-1} = mc^2/E$ as shown in a **Figure 2**. Due to the collimation of radiated photons in such a small angle, cone results in highly intense beam and power radiations in forwarding direction even at distance of tens of meters from storage ring [1–3].

According to special theory of relativity, the kinetic energy of a particle having rest mass *m* moving with velocity *v* is given ≪ by [5]:

$$\begin{aligned} E &= \frac{\mathrm{mc}^2}{\sqrt{1-\left(\frac{\mathrm{v}}{\mathrm{c}}\right)^2}} \\ &= \frac{mc^2}{\sqrt{1-(\beta)^2}} \end{aligned} \tag{1}$$

$$\gamma = \frac{1}{\sqrt{1-(\beta)^2}} \tag{2}$$

where $\beta = v/c$ and γ is relativistic correction factor. If the particles approach the speed of light, their mass becomes multiple of factor γ. The particle would have gained infinite mass at $v = c$, which means that the β is a prime factor to consider for the synchrotron radiation. From the above relation, we can write β as

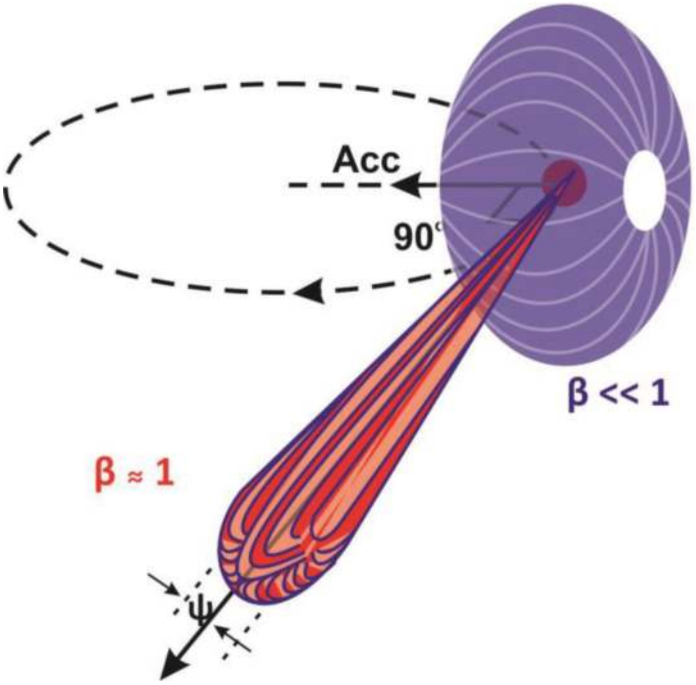

Figure 2.
Radiation pattern of charged particles moving in a circular path: blue ($\beta \ll 1$) and red ($\beta \approx 1$).

$$\beta = \left(1 - 1/\gamma^2\right)^{1/2} \tag{3}$$

For the case of relativistic energy, $1/\gamma^2$ is too small, and the above Taylor expansion can be solved by ignoring the higher terms as

$$\beta \approx \left(1 - \frac{1}{2\gamma^2}\right) \tag{4}$$

In the storage ring, electrons are traveling in a closed path under the effect of the magnetic field which applies a Lorentz force normal to the motion of the charged particle and the magnetic field vector. As the orbital radii (r) remain constant, we can equate the Lorentz force to centripetal force under classical regime as

$$e\,\vec{v} \times \vec{B} = \frac{mv^2}{r} \tag{5}$$

In case of $\beta \approx 1$, m and v must be replaced by the relativistic mass γm and c, respectively. Therefore,

$$ecB = \frac{\gamma mc^2}{r} \tag{6}$$

$$\begin{aligned} \Rightarrow \mathrm{r} &= \frac{\gamma mc}{\mathrm{eB}} \\ &= \frac{E}{ecB} \end{aligned} \tag{7}$$

So, in terms of standard synchrotron practical units, the above equation can be rewritten as

$$r[m] = 3.3\,\frac{E[GeV]}{B[T]} \tag{8}$$

This implies that the magnetic lattice and storage ring's radius set the limits to the beam energy. The characteristic frequency Ω_c of a synchrotron source in terms of γ and Ω_0 is given as

$$\Omega_c = \frac{3}{2}\gamma^3\Omega_0 = \frac{3}{2}\gamma^3\frac{c}{r} \tag{9}$$

Using the above formulations, we can write the critical energy of a synchrotron light source which is exactly half of the total power emission from a bending magnet as

$$\hbar\Omega_c[keV] = 0.665\,E^2[GeV]B[T]. \tag{10}$$

There are basically two important quantities which can be used to characterize the properties of emitted beam from various light sources: flux and brilliance. The flux is defined as the total number of photons per second per unit *0.1*\% bandwidth radiated in unit angular spread θ along the orbital plane and integrated over the vertical ψ opening angle [1–5]:

$$Flux = \frac{d\phi}{d\phi}\ [\mathrm{photons/s/0.1\%bw/mrad}\ \theta]$$

$$Brilliance = d^4\phi/d\theta d\psi dxdz\ \left[\mathrm{photons/s/0.1\%bw/mrad^2}\right] \tag{11}$$

Brilliance/brightness of the emitted radiation beam has been enhanced over the years as the technology evolves as shown in **Figure 3**. The synchrotron sources enhanced the brilliance of radiations 20 times than that of X-ray tubes/laboratory-based sources. Due to such a high brilliance, synchrotron radiations are able to explore the deep-inside of materials properties and of utmost interest of scientific research community. In third-generation synchrotron source, both of these quantities can be tuned according to the experimental requirement. The important parameters of the world's top third-generation synchrotron light sources in decreasing order of their storage ring energy are listed in **Table** 1 [2, 4, 6]. Insertion devices have been installed in the storage ring to enhance the flux and brilliance of photon beam.

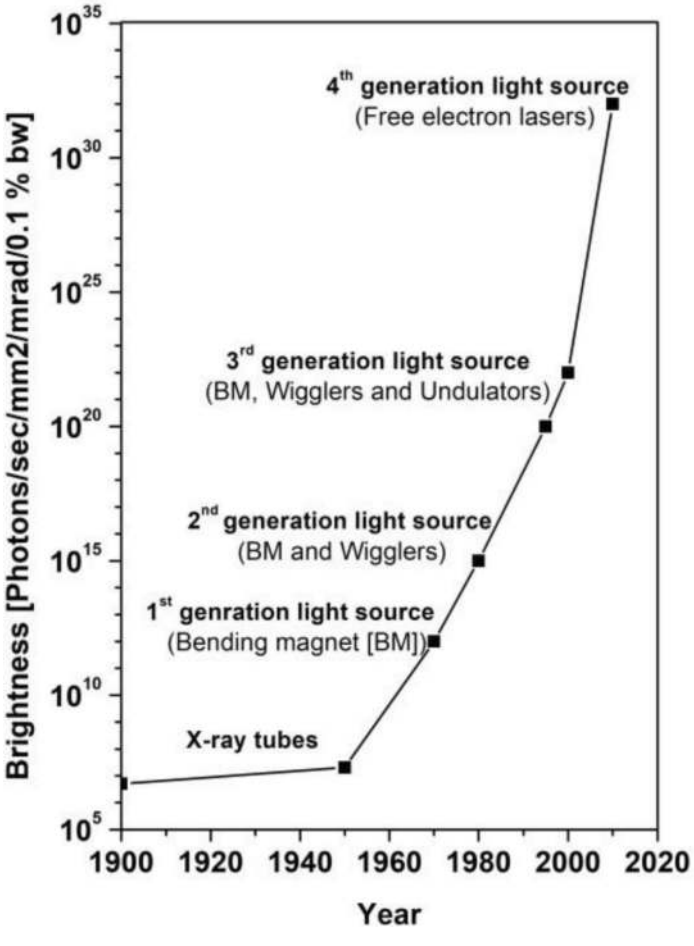

Figure 3.
Evolution of brightness of emitted radiations from the different technical sources over time.

Facility	Country	Energy [GeV]	Current [mA]	Periphery [m]	Emittance [nm-mrad]	Brilliance [ph/s/mrad^2/mm^2/0.1%bw]
Spring8	Japan	8.00	100	1436.00	2.80	2.0×10^{21}
APS	USA	7.00	100	1104.00	3.00	8.0×10^{19}
PF-AR	Japan	6.50	60	377.00	294.00	4.0×10^{13}
ESRF	France	6.00	200	844.00	3.80	8.0×10^{20}
PETRA-III	Germany	6.00	100	2304.00	1.00	2.0×10^{21}

Facility	Country	Energy [GeV]	Current [mA]	Periphery [m]	Emittance [nm-mrad]	Brilliance [ph/s/ mrad^2/mm^2/0.1%bw]
CHESSS	USA	5.29	200	768.43	101.70	10^{15}
SSRF	China	3.50	300	432.00	3.90	10^{20}
Candle	Armenia	3.00	350	216.00	0.08	1.7×10^{13}
AS	Australia	3.00	200	216.00	7.00	4.6×10^{18}
Diamond	England	3.00	300	562.00	2.70	3.0×10^{20}
SLAC	USA	3.00	500	234.00	0.01	2.0×10^{13}
PAL	South Korea	3.00	400	281.82	5.80	2.0×10^{11}
ALBA	Spain	3.00	100	268.80	4.58	4.0×10^{12}
NSRRC	Taiwan	3.00	500	518.40	1.60	10^{16}
NSLS-II	USA	3.00	500	792.00	0.60	3.0×10^{21}
CLS	Canada	2.90	250	171.00	18.10	1.5×10^{11}
SOLEIL	France	2.75	500	354.00	3.70	10^{20}
ANKA	Germany	2.50	200	110.00	50.00	10^{18}
INDUS-II	India	2.50	200	110.00	50.00	10^{13}
PF	Japan	2.50	450	187.00	36.00	3.0×10^{14}
Elletra	Italy	2.40	320	260.00	7.00	10^{19}
SLS	Switzerland	2.40	400	288.00	5.50	5.0×10^{15}
BSRF	China	2.20	100	240.40	7.60	7.0×10^{12}
MAX-IV	Sweden	2.00	500	528.00	0.17	2.2×10^{21}
ALS	USA	1.90	100	240.00	6.80	3.0×10^{18}
BESSY-II	Germany	1.70	100	240.00	6.00	5.0×10^{18}
SAGA	Japan	1.40	300	75.60	25.00	10^{13}

Table 1.
Important parameters of the world's top third-generation synchrotron light sources, tabular in order to decrease storage ring energy [2, 4, 6].

3. Bending magnet/superbend source

The bending magnets (BM) in the storage rings are the primary sources of radiations. Although the primary aim of the (BM) is to circulate the e^{-}-beam in a closed path, as an e^{-} is forced to move in an arc through the magnetic field by BM, it produces radiation in a flattened cone [1–3]. The BM source produces a beam of fixed vertical opening angle $\psi \sim \gamma^{-1}$ (photon beam divergence), while the horizontal spam is determined by the length of the BM arc. The critical energy of a synchrotron source depends upon the storage ring energy and the magnetic field of BM. The flux spectrum of a source of BM having different magnetic field strength is shown in **Figure 4**. But the technology imparts limits to field strength of permanent magnets ≈ 1 T; only electromagnets made up of superconductor materials (niobium alloys) under cryogenic temperature (liquid He cooling) can provide the field

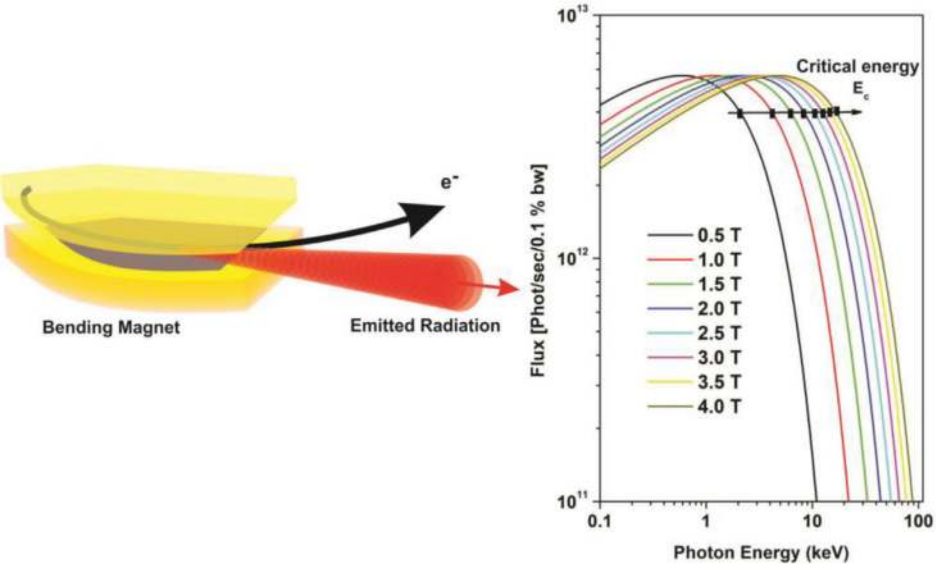

Figure 4.
Pictorial representation of generation of X-ray beam from bending magnet source and the comparative change in the flux spectrum as a function of BM field strength. Graph shows the enhancement in the critical energy with magnetic field strength.

strength of ∼ 5 T [2, 7], called superbend source. In this manner, the critical energy of a synchrotron source can be enhanced to 4–5 times.

4. Insertion devices

Insertion devices are the magnetic devices which can supply periodic magnetic fields on the e$^-$-beam through the straight section of the storage ring [1]. The so-called terminology "insertion devices" is used due to its characteristic role, which can be added or replaced from drift space between two bending magnets without perturbing normal operation. There are basically two types of insertion devices: (1) wiggler and (2) undulator, which have been designed to enhance the characteristics (flux, brilliance, energy) of the radiated photon beam [1–3, 6].

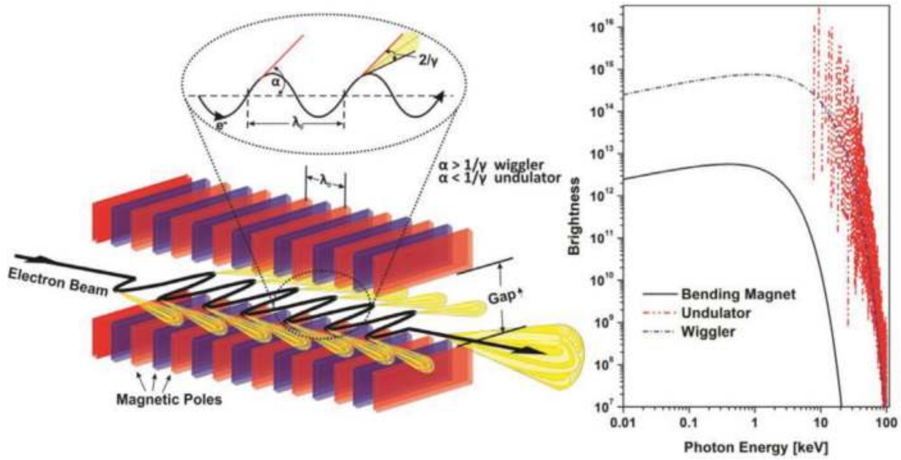

Figure 5.
Layout of radiation beam emission from permanent multipole wiggler/undulator insertion devices used in most of the third-generation synchrotron light sources. The brightness spectrum of the emitted radiations from the individual device source has been shown.

A wiggler is a multipole magnet having periodic (N) arrangement of length (λ), through which it forced an electron to periodically wiggle around its natural path as shown in **Figure 5**. Each wiggle acts as a bending magnet source, so the superposition of radiation from each wiggle enhances the flux and brilliance which is directly proportional to the number of poles N and corresponding magnetic field strength [6]. The horizontal spam of wiggler radiation is defined by $K\gamma^{-1}$, where K is the magnetic deflection parameter and defined as the ratio of wiggling angle (α) of trajectory to the angular aperture (1/γ) given as

$$K = \alpha\gamma \tag{12}$$

An undulator is working on the same principle of wiggler, but $\alpha \le \gamma^{-1}$ and $K \ll 1$ as shown in **Figure 5**. In this condition, radiated photon loops overlap and interfere with each other along the trajectory. Due to the interference effect in the emitted radiations by individual poles in undulator, it produces the pseudo-monochromatic energy bands called harmonics.

5. Double-crystal monochromator

Synchrotron radiations deliver many features (continuous energy spectrum, high flux, highly collimated and polarized radiation) which are of intense concern in X-ray experimentations. In order to employ this radiation source for the broad area of X-ray scattering/absorption experiments, one has to optimize the various parameters of synchrotron radiations [5]. As for diffused scattering, high flux and low-energy resolution beam are required, while for inelastic scattering high-energy resolution is required. Synchrotron radiations are highly tunable and can be optimized by proper selection of optical design in the beamlines [3, 6].

In condensed matter physics/material science, most experiments required a wide energy range, high-energy resolution/precision, high flux, and focusing. In particular, a monochromator plays an important role to tune the energy of radiation emitted by BM, wiggler, and undulator [7, 8]. BM and wiggler radiate a continuous energy spectrum known as a white beam, while undulator produces pseudo-monochromatic energy bands.

In general, most of the monochromators have two-bounce geometry called double-crystal monochromator [3]. In this geometry, the first crystal diffracts the energy spectrum as a function of incident angle and monochromatizes the synchrotron radiation, while the second crystal adjusts the beam height and direction as

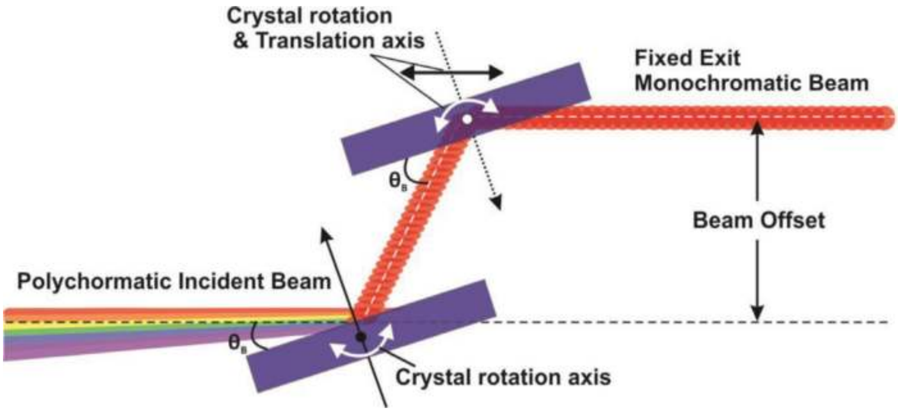

Figure 6.
Geometry of fixed-exit double-crystal monochromator (DCM) system.

shown in **Figure 6**. The energy tuning can be achieved by the crystal's plane rotation and horizontal focusing by sagittal bending of the second crystal [2].

The choice of the crystal is favored by the available crystal quality, thermal conductivity, and its ability to resist from radiation damage [3]. Silicon crystal is widely used due to its relatively high abundance, high thermal conductivity, and mass production as a perfect single crystal of tens of centimeter because of its intense use in the semiconductor industry. As the energetic radiations fall on the crystal, lose energy, and make surface hot, the liquid nitrogen cooling is required to minimize the mechanical strain prompt by incident radiations.

6. Conclusions

In this chapter, the generation of emitted radiations from the different sources has been discussed. The effect of individual source on the emitted radiation brilliance has been studied and provides the understanding of choosing the correct source for particular applications. Such high brilliance of synchrotron light sources makes it a likely/suitable candidate for real-time investigation of materials as compared to that of laboratory-based/X-ray tube sources.

The synchrotron beamlines are dedicatedly designed for specific applications, i.e., X-ray imaging (tomography), X-ray absorption spectroscopy (X-ray absorption fine structure (XAFS), near-edge and extended-edge spectroscopy (XANES, EXAFS)), X-ray scattering (small- and wide-angle X-ray scattering), and X-ray fluorescence/emission spectroscopy (XRF). Moreover, a single beamline can be utilized as a simultaneous multi-characterization tool that would definitely explore the insight of new physics of devices.

This works gives an insight to the basic understanding of the generation of synchrotron radiations and its tunable characteristics via insertion devices which is the fundamental requirement of X-ray spectroscopy.

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