Hard X-ray Sources for the Mexican Synchrotron Project

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Abstract. One of the principal tasks for the design of the Mexican synchrotron was to define the storage ring energy. The main criteria for choosing the energy come from studying the electromagnetic spectrum that can be obtained from the synchrotron, because the energy range of the spectrum that can be obtained will determine the applications available to the users of the future light source. Since there is a public demand of hard X-rays for the experiments in the synchrotron community users from Mexico, in this work we studied the emission spectra from some hard X-ray sources which could be the best options for the parameters of the present Mexican synchrotron design. The calculations of the flux and the brightness for one Bending Magnet and four Insertion Devices are presented; specifically, for a Superconducting Bending Magnet (SBM), a Superconducting Wiggler (SCW), an In Vacuum Short Period Undulator (IV-SPU), a Superconducting Undulator (SCU) and for a Cryogenic Permanent Magnet Undulator (CPMU). Two commonly available synchrotron radiation programs were used for the computation (XOP and SRW). From the results, it can be concluded that the particle beam energy from the current design is enough to have one or more sources of hard X-rays. Furthermore, a wide range of hard X-ray region can be covered by the analyzed sources, and the choice of each type should be based on the specific characteristics of the X-ray beam to perform the experiments at the involved beamline. This work was done within the project Fomix Conacyt-Morelos "Plan Estratégico para la construcción y operación de un Sincrotrón en Morelos" (224392).

1. Introduction

A typical storage ring light source consists of a source, an injector, transport lines between accelerators, a storage ring, and a collection of surrounding beamlines with their experimental stations. A basic storage ring scheme with some synchrotron radiation sources is shown in the Figure 1.

In the present, there are three main groups of synchrotron sources based on storage rings. These are classified by the electron beam energy, low energy storage rings (<2 GeV) for VUV and soft X-rays radiation, high energy (6-8 GeV) for hard X-rays radiation, and the intermediate-energy light sources (2.5 GeV to 3.5 GeV); the Mexican project has been planned to be an intermediate-energy light source (ILS). Besides the good profitability of the ILS [2], there are other reasons for the popularization of the ILS around the world. This popularity is largely based on the high performance of these machines, backed up by recent technology developments like better systems to control instabilities at high beam current, higher harmonic RF-cavities

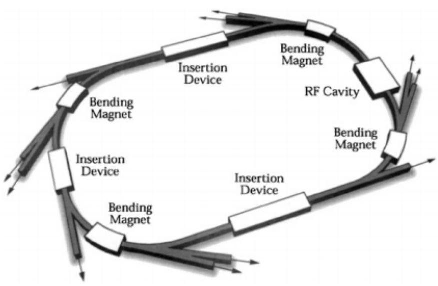

Figure 1. Basic components of a storage ring light source. The injection system is not shown [1].

to extend beam life time, between others [3]. One of the most important technological improvements was the development of insertion devices (IDs) to generate plentiful hard X-rays at relatively low electron beam energy [1]. This progress allows ILS to deliver hard X-rays (5-50 keV) [3].

There are many synchrotron radiation sources (bending magnets and IDs) that can provide hard X-rays in an ILS facility. The main target of this work is to study these sources under the electron beam parameters of the Mexican synchrotron design.

2. Hard X-ray sources for ILS

The radiation from bending magnet (BM) and wiggler sources is a continuum spectrum with a critical photon energy ε_c,

$$\varepsilon_c(\text{keV}) = 0.665 B(\text{T}) E^2(\text{GeV}), \tag{1}$$

where E is the electron beam energy and B is the magnetic field of the bending or wiggler magnet. The high magnetic field of the wiggler can extend the radiation to higher photon energy compared to a dipole. The radiation spectrum from an undulator magnet consists of a series of discrete harmonic peaks with the photon energy of ε_n [5],

$$\varepsilon_n[\text{keV}] = \frac{0.95 n E^2[\text{GeV}]}{\lambda_u[\text{cm}](1 + K^2/2)}, \tag{2}$$

where λ_u is the undulator period (Figure 2), n is the radiation harmonics, and $K = eB\lambda_u/2\pi\beta mc$ is the undulator magnetic strength parameter, where β is the relative speed of the electron with respect to the light.

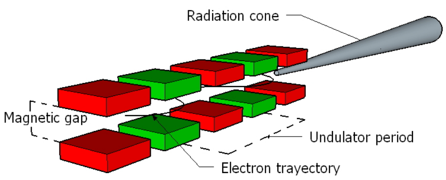

Figure 2. Magnetic structure of an Undulator.

Two important figures of merit for synchrotron radiation are the spectral photon flux F, defined as the photons emitted by electron beam per second and in 0.1% bandwidth, and the spectral brightness $\mathbf{B}$, defined as the photon flux per unit source area and per unit solid angle of the radiation cone [4],

$$F = \frac{N_{ph}}{0.1\% \Delta\omega/\omega}, \tag{3}$$

$$\mathbf{B} = \frac{N_{ph}}{4\pi^2 \sigma_{Tx}\sigma_{Tx'}\sigma_{Ty}\sigma_{Ty'} 0.1\% \Delta\omega/\omega}, \tag{4}$$

where N_{ph} is the number of photons per second and $\sigma_{Tx}\sigma_{Tx'}\sigma_{Ty}\sigma_{Ty'}$ are the effective photon beam sizes and divergences in transverse planes.

It can be noticed from the equations (1) and (2) that in order to obtain higher X-ray energies, it is necessary to increase either the electron beam energy (E), the magnetic field (B) or, to decrease the λ_u in the case of an Undulator. Since the cost of a synchrotron facility notably increases at higher electron beam energies, in the present there exists a good variety of technologies aimed to have IDs and BMs with stronger magnetics fields and shorter undulator periods as hard X-ray sources. The devices that could have good potential (as hard X-rays sources) for the Mexican light source project are

(i) High field bending magnets or Super-Bending Magnets (SBMs).
(ii) SuperConducting Wigglers (SCWs).
(iii) In Vacuum Short Period Undulators (IV-SPUs).
(iv) Superconducting Undulators (SCUs).
(v) Cryogenic Permanent Magnets Undulators (CPMUs).

2.1. High field bending magnets or Super-Bending Magnets (SBMs)
Some light sources around the world are using, or planning to use, SBMs, these SBMs can produce high magnetic fields based on super-conducting materials. For instance, there is a proposal in the SIRIUS (Brazil) designed to use SBMs of 2 T to generate hard X-rays [6]. Another case is in the SSRF (China) where the researchers are planning an upgrade of the sources by replacing normal BMs by SBMs [7]. Since there is a intrinsic spreading in a cone of the radiation from a magnetic dipole, this kind of sources can be used in experiments where hard X-rays are required but not needed with high brightness.

2.2. Super-Conducting Wigglers (SCWs)
There are many ILS using SCWs to generate hard X-rays, some of them are shown in the table 1. It is worth to mention that this SCWs were built in the Budker Nucler Physics Institute, Novosibirsk, Russia [8].

Table 1. Examples of SCWs installed at some ILS: the Canadian Light Source (CLS), the English Source (DLS), the Italian (Elettra) and the Spanish synchrotron (ALBA). Here E_e is the electron beam energy and E_p is the photon energy.

Synchrotron	E_e (GeV)	Beamline	E_p (keV)
CLS	2.9	BMIT	20-100
DLS	3	I12	50-150
Elettra	2.4	XRD2	8-30
ALBA	3	BL04 MSPD	8-50

Due to its low operating temperature (4 K), the manufacturing and operation of the SCWs are significantly higher than those based on permanent magnets. For these reasons, there are many efforts to build a Wiggler with high magnetic fields using permanent magnets only [9].

2.3. In-Vacuum Short Period Undulators (IV-SPUs)
The Undulators (hybrids or pure structure) are the workhorses of every third generation synchrotron facility. However most of them have long undulator period and big magnetic gaps, making impossible to generate high brightness hard X-rays for an ILS. To reduce the magnetic gap of these devices, the magnetic structure can be placed inside the vacuum chamber (In-vacuum Undulators). Therefore, in principle, the magnetic gap is limited only by the electron beam acceptance. Additionally, if the Undulator period is short, this ID can be an improvement of the hard X-rays brightness in a ILS [10]. There is an excellent explanation of the advantages and disadvantages of the use of IV-SPUs in the work by Hwang *et al* [10].

2.4. SuperConducting Undulators (SCUs)
The use of Undulators as hard X-rays sources carries some costs, first, reducing λ_u reduces K proportionally, resulting in fewer emitted photons with high energy. Both electromagnet and permanent-magnet based Undulators are material limited in their maximum magnetic field strength B, so there is no obvious way to compensate for this reduction in K. There are also some practical challenges. To maintain sufficient magnetic field strengths, the undulators air gap (between top and bottom magnet arrays) must also be scaled down proportionally. This narrowed gap demands strict beam alignment and low beam emittance in order to pass the electrons through the structure without beam scraping [11]. These difficulties can be avoided by the use of superconducting materials to get high magnetic fields. Since 1990 many proposals appeared, about the replacement of permanent magnets by superconducting wires or coils [12] y [13]. There is a complete study about NbTi and Nb_3Sn SCUs made by J. Bahrdt and Y. Ivanyushenkov [14], in this work they concluded that the SCU technology permits an excellent spectral performance, and the SCUs will become the preferred devices as soon as operational issues have been demonstrated in a multi-user facility.

2.5. Cryogenics Permanent Magnets Undulators (CPMUs)
Another option is to use short period Undulators based on permanent magnets, for short Undulator periods ($\lambda \leq 9$ mm) the CPMUs can reach the same magnetic field intensity than the SCUs [14]. Since the operation temperature of the CPMUs is around the liquid nitrogen temperature, the operation costs and the heating problems are fewer than with the SCUs. Another advantage of the CPMUs over the SCUs is that the field correction techniques developed for conventional permanent magnet Undulators can be directly applied to the CMPUs [15]. Currently, there are many CPMUs devices under development at some light sources in the world, for example the ones at SOLEIL [16] and the ESRF [17]. There are promising results and it seems like the CPMUs will dominate the short period undulator technology for the next years [14], for storage rings [18] and for free electron lasers (FELs) [19].

3. Spectra calculations from the sources
The parameters of the storage ring design are shown in the table 2.

Using the codes XOP (X-ray Oriented Programs, see 2.3) [20] and SRW (Synchrotron Radiation Workshop, see 3.92) [21] the flux and brightness from some sources are shown in the figures 3 and 4, respectively.

4. Conclusions
The study of different hard X-ray sources for the Mexican synchrotron project has been done. From the calculated spectra it can be concluded that the parameters of the present storage ring design are enough to have one or more hard X-rays sources for the users. The hard X-rays region can be covered from the studied sources, each of these has some advantages and disadvantages and the election will depend on the specifications needed from the corresponding beamline.

Table 2. Electron beam parameters of the Mexican source project, corresponding to the straight sections of the storage ring.

Beam Energy	E_e= 3 GeV
Circumference	300 m
Beam current	I= 0.250 A
Horizontal emittance	ε_x= 1.1 nm rad
Vertical emittance	ε_y= 0.161 pm rad
Horizontal β function	β_x= 2.06 m
Vertical β function	β_y= 1.32 m

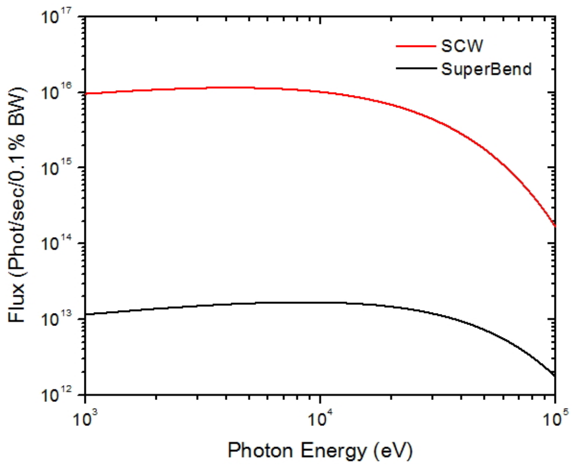

Figure 3. Flux from a 5 T Super bend (ALS [22]) and a SCW (Elettra [23]).

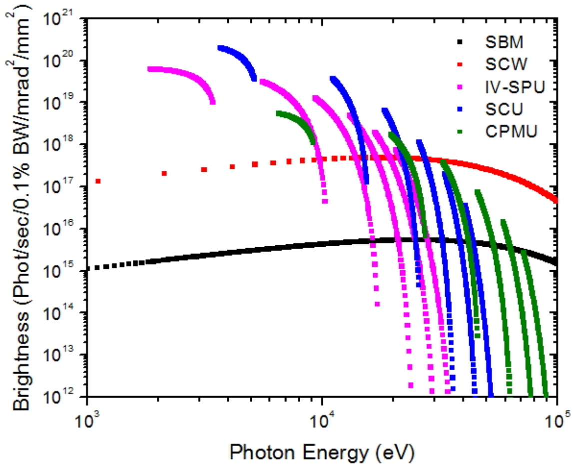

Figure 4. Brightness spectra from a 5 T Super-Bend (ALS [22]), a SCW (Elettra [23]), a IV-SPU (Diamond [24]), a SCU (APS [25]) and a CPMU (under development at the HZB [26]).

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[1] J. Corbett, T. Rabedeau 2003 *Nucl. Instrum. Methods* A **500** 11
[2] Z.T. Zhao 2010 *Reviews of Accelerator Science and Technology Vol. 3* (World Scientific Publishing Company) 57
[3] W. A. Barletta, H. Winick 2003 *Nucl. Instrum. Methods* A **500** 1
[4] H. Wiedemann 2002 *Handbook of Accelerator Physics and Engineering* (World Scientific) 184
[5] H. Onuki, P. Elleaume 2003 *Wigglers, Undulators ant their Applications* (Taylors and Francis, USA, Canada)
[6] L. Liu, X. R. Resende, R. D. Rodrigues 2010 *Proccedings of IPAC'10* Kyoto, Japan, 2481
[7] Tian Shun-Qiang *et al* 2014 *Nucl. Science and Tech.* **25** 010102
[8] S. Khruchechev *et al* 2014 *Proccedings of IPAC2014* Dresden, Germany, 4103
[9] J. Chavanne, P. Van Vaerenbergh, P. Elleaume 1999 *Nucl. Instrum. Methods* A **421** 352
[10] C.S. Hwang, J.C. Jan, S.D. Chen, C.H. Chang, and T.M. Uen 2011 *Phys. Rev. ST Accel. Beams* **14** 044801
[11] B. A. Peterson *et al* 2014 *Physics Procedia* **52** 36
[12] I. Ben-Zvi, Z.Y. Jiang, G. Ingold, L.H. Wu 1990 *Nucl. Instrum. Methods Phys. Res.* A **297** 301.
[13] H.O. Moser, B. Krevet, H. Holzapfel, *Research Center Karlsruhe* German Patent No. DE 4101094
[14] J. Bahrdt, Y. Ivanyushenkov 2013 *J. Phys.: Conf. Ser.* **425** 032001
[15] T. Hara, T. Tanaka, H. Kitamura, T. Bizen, X. Marchal, T. Seike, T. Kohda, Y. Matsuura 2004 *Phys. Rev. ST Accel. Beams* **7** 050702
[16] C. Benabderrahmane *et al* 2013 *J. Phys.: Conf. Ser.* **425** 032019
[17] J. Chavanne, M. Hahn, R.Kersevan, C.Kitegi, C.Penel, F.Revol 2008 *Proceeding of EPAC Conf.* Genova, Italy 2243
[18] F. Holy *et al* 2014 *Phys. Rev. ST Accel. Beams* **17** 050704
[19] F.H. O'Shea, G. Marcus, J. B. Rosenzweig, M. Scheer, J. Bahrdt, R. Weingartner, A. Gaupp, F. Grner *Phys. Rev. ST Accel. Beams* **13** 070702
[20] M. Sanchez del Rio, R.J. Dejus 2004 *SPIE Proceedings Vol.* **5536** 171
[21] O. Chubar, P. Elleaume 1998 *Proc. of the EPAC98 Conference* 1177
[22] D. Robin, *et al* 2002 *Proceedings of EPAC 2002* Paris, France 215
[23] L. Tosi, C. Knapic, D. Zangrando 2004 *Proceedings of EPAC 2004* Lucerne, Switzerland 390
[24] J. A. Clarke, N. Bliss, D. G. Clarke, F. E. Hannon, C. Hill, A. A. Muir and D. J. Scott 2003 *Proceedings of the 2003 Particle Accelerator Conference* 1029
[25] Y. Ivanyushenkov *et al* 2015 *Phys. Rev. ST Accel. Beams* **18** 040703
[26] F. Holy *et al* 2014 *Phys. Rev. ST Accel. Beams* **17** 050704