An-Najah University Journal for Research – A

Natural Sciences

Field Hybrid Permanent Magnet Wiggler Optimized for Tunable Synchrotron Radiation Spectrum

Received: (1/12/2022), Accepted: (31/1/2023), DOI: 10.35552/anujr.a.37.1.2099

Ahmed Bassalat[1,*], Hadil Abualrob[1]

Abstract: Synchrotron radiation provides a powerful tool of high brightness and tunable energy range for scientific applications in different domains such as chemistry, biology, material science and many others. The scientific community has recently shown a great interest in high-energy photons for other applications such as archaeological studies. To meet different demands, this study gives two proposals: called proposal 1: wiggler of 164 mm period and proposal 2: wiggler 98 mm period. Each proposal provides a single insertion device that can operate in the wiggler regime at high-energy range and in the undulator regime at low-energy range by simple gap adjustment. It develops the concept of insertion devices, gives a detailed study of the possible technologies, provides a simulation of the emitted photon flux by the proposed insertions, and compares the emitted radiation of each of them. It is found that proposal 1 provides 10^5 more flux in the undulator regime and 10 times more flux in the wiggler regime.

Keywords: Insertion device, Wiggler, Undulator, Synchrotron Radiation.

Introduction

Synchrotron radiation can be generated by accelerated charged particles travelling in magnetic field perpendicular to their direction of motion. This process provides radiation of unique characteristics over traditional light sources. Synchrotron radiation is of high intensity and covers a large spectral range, from far infra red to hard X-ray [1]. Third generation synchrotron radiation sources are storage rings like SOLEIL (France) [2], MAX IV (Sweden) [3], and SESAME (Jordan) [4]. In a typical third generation light source, an electron beam circulates at energy of few GeV and radiation is mainly produced by electrons being accelerated through insertion devices: magnetic systems composed of series of dipoles of alternating polarities that generate a periodic magnetic field. At each dipole, the electron beam is deflected and a light wave of small aperture is emitted. The emitted light waves overlap and the photon flux (number of photons emitted per second per spectral bandwidth) adds up producing at the end synchrotron radiation of high flux. In general, insertion devices include two types: undulators and wigglers. The principle of an undulator was first proposed by V. Ginsburg in 1947 [5] in a 70 MeV synchrotron by the General Electric Society in New York (USA). The idea of using a magnetic system composed consecutive magnetic fields of alternative polarities in order to obtain radiation with higher intensity than that obtained from bending magnets was developed in [6].

According to the magnetic field they generate, two types of insertion devices are distinct: planar and elliptical. A planar insertion device generates magnetic field vector in a constant plane, most commonly the vertical plane. An electron beam propagating through such device follows a sinusoidal trajectory in the plane perpendicular to the plane of the magnetic field. Elliptical insertion devices generate a magnetic field of variable direction along the horizontal (x) or the vertical (z) axis with ϕ phase advance between the field components. The trajectory of the electron beam propagating through an elliptical insertion device is helical around its axis. According to the adopted technology, different types of insertion devices are distinct: electromagnets, permanent magnets and superconducting magnets. Fig.

1 Physics Department, An-Najah National University, Nablus, Palestine.
* ahmed.bassalat@najah.edu

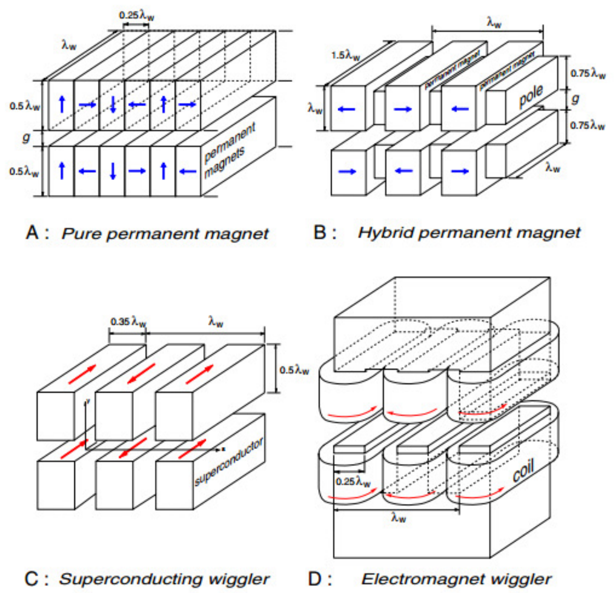

FIG. 1: Common magnetic designs and dimensions of insertion devices. Blue arrows indicate the magnetization direction, red arrows indicate the current direction [7].

1 shows common magnetic design for different insertion devices technology. Electromagnetic insertion devices consist of copper coils of alternated polarities that generate a varying magnetic field based on the circulating current. Pure permanent magnet (PPM) insertion devices are composed of two parallel arrays of permanent magnets and the magnetic field is varied by adjusting the gap; i.e. the separating distance between the two magnetic arrays. The magnetic field of a planar device can be enhanced by inserting ferromagnetic poles between the permanent magnets. In this case, it is called hybrid permanent magnet (HPM) technology. The applications of the superconducting magnets are limited by the high cost.

This work is a study of a high field hybrid permanent magnet wiggler with planar configuration that can operate both in the undulator and the wiggler regime. The undulator-wiggler regime transition is made possible by tuning its magnetic field that can be tuned by a simple adjustment of its gap. The proposed wiggler is based on the magnetic field of a planar wiggler given by Halbach formula [8] in terms of its period and gap in addition to other parameters calculated in [9] for different wiggler technologies. We give two proposals for an insertion device that operates in both the wiggler and the undulator regimes and fulfills the gap to period ratio condition. Then we compare their performance in terms of the emitted radiation.

Radiation from insertion devices

Electromagnetic radiation emitted by accelerated electrons through insertion devices are concentrated in a narrow cone with an opening angle of $\frac{1}{\gamma}$ (γ is Lorentz factor). The radiation cones are centered around the tangent to the particle trajectory with angle θ with respect to the beam axis. As the direction of the tangent varies along the sinusoidal trajectory, the emission angle θ varies accordingly. Therefore, the emitted radiation receives contributions from various sections of the trajectory that interfere with each other. Constructive interferences between the emitted radiation from different periods take place only if the resonance condition is satisfied. The resonance condition implies that the temporal delay between the emitted light waves must be an integer number of the temporal period of the wave. Radiation is emitted at the resonance wavelength and its harmonics:

$$\lambda_R = \frac{\lambda_0}{2n\gamma^2}(1 + \frac{K^2}{2} + \gamma^2\theta^2) \qquad (1)$$

with n the harmonic number, λ_0 the magnetic period, γ the relativistic factor, θ the observation angle and K the deflection parameter defined as:

$$K = \frac{eB\lambda_0}{2\pi m_0 c} \qquad (2)$$

with e the electron charge, m_0 its rest mass, c the speed of light in vacuum and B the magnitude of the magnetic field.

The spectral angular flux emitted by an insertion device is made up of a series of harmonics with λ_1 the wavelength of the fundamental harmonic. Higher order harmonics are of wavelength equals to a multiple integer of the fundamental harmonic. In the forward direction only odd higher harmonics are observed while the off-axis radiation contains both even harmonics and the odd ones.

As the emitted radiation is the contributions from various sections of the electron trajectory, the radiation spectrum in the forward is composed of a narrow spectral line at the resonance wavelength and its harmonics. This is called the undulator regime. However, if the maximum emission angle exceeds the radiation cone angle by a large factor, the regime is called the wiggler regime.

In the undulator regime the angular deviation is close to the angle of the emitted cone, so interferences occur between the radiation emitted by the same electron at different points. Consequently, the amplitude of the fields (radiation cones) adds up coherently and the intensity increases with N_0^2 [10]. N_0 is the number of periods of the insertion device . In the wiggler regime,

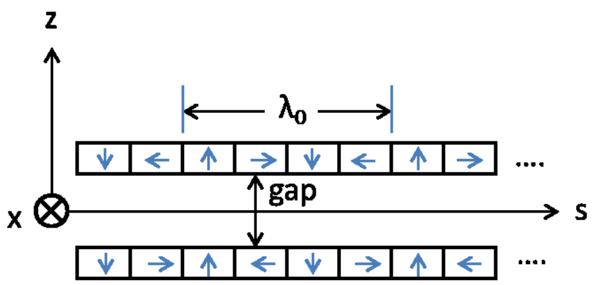

FIG. 2: Schematic presentation of Halbach pure permanent magnet insertion device based on 8 magnets per period. The arrows show the magnetization direction of the permanent magnets.

the transverse oscillations of the electrons are very large and the angular deviation with respect to the axis is much wider than the natural opening angle of the radiation cone. For that reason, interference effects between the emission from the different poles can be neglected and the flux output is obtained by summing the contribution of the individual poles. Hence, the intensity increases with $2N_0$ [10].

Hybrid permanent magnet (HPM) insertion devices

The magnetic field generated by an electromagnetic insertion device can be varied by tuning the current circulating in the coils. However, the maximum current density achieved at room temperature is limited to 20 A/mm^2 [11]. Therefore, electromagnet technology is restricted for long periods low fields insertion devices. Another limitation of this technology is the high running cost due to the high power consumption [12]. Superconducting coils can provide a solution to achieve deliver higher current density [13]. A Superconducting wigglers can achieve a peak field as high as 10 T [14].

Permanent magnets are made of rare earth materials. The most common materials are Samarium Cobalt [15] and Neodyme-Fer-Bore ($Nd_2Fe_{14}B$) [16]. Pure permanent magnet (PPM) insertion devices were first proposed by Halbach [8] based on building an insertion device with two parallel arrays of permanent magnets as shown in fig. 2. The magnetization direction from one permanent magnet to the next is rotated by 90°. The most common case of Halbach structure is based on 8 magnets per period λ_0. The magnetic field is varied by adjusting the gap; i.e. the separating distance between the two magnetic arrays.

Hybrid Permanent Magnet (HPM) technology [17] allows for increasing the magnetic field of the insertion device by enhancing the magnetic induction. This is made possible by inserting poles made of ferromagnetic material such as Iron and Vanadium Permandur (iron-cobalt alloy) between the permanent magnets. In addition to the field enhancement, the magnetic field imperfections seen by the electrons are less sensitive to the in-homogeneity of the magnetization of the blocks. However, the HPM technology is more expensive due to the high cost of the inserted poles.

According to Halbach, the on-axis peak magnetic field of a planar wiggler for each type of the previous technologies is related to the wiggler gap g and period λ_0 by as:

$$\hat{B} = a \;\; exp. \left[b \left(\frac{g}{\lambda_0} \right) + c \left(\frac{g}{\lambda_0} \right)^2 \right] \qquad (3)$$

where a, b and c are parameters that depend on the wiggler performances and the magnet material. a is given in units of Tesla, b and c are unitless. These parameters were studied and calculated using RADIA in [9] for different kinds of planar wigglers leading to coefficients a, b and c presented table I.

The peak field variation as a function of the ratio $\frac{g}{\lambda_0}$ according to table I for different wiggler technologies is shown in fig. 3. The use of the coefficients a, b, c, allows for a direct peak field calculation and facilitates the selection of the suitable wiggler technology without dealing with magnetostatic codes like RADIA.

Results and analysis

Fig. 3 shows that electromagnet and superconducting technologies are less efficient in producing the required magnetic field at small gap to period ratio; i.e $g/\lambda_0 < 0.1$. PPM provides higher field than electromagnetic and superconducting technologies. The material from which the magnets are made plays an important role in the field quality. Wigglers constructed from $Nd_2Fe_{14}B$ produce higher field than those constructed from Sm_2Co_{17} magnets, because $Nd_2Fe_{14}B$ has a higher magnetic remanence. However, Sm_2Co_{17} magnets are less sensitive to radiation damage and more resistant at high temperatures compared to the more common $Nd_2Fe_{14}B$ [18]. The $Nd_2Fe_{14}B$ material used in the computation (fig. 3) has a remanence of 1.2 T. Fig. 3 shows that adopting a hybrid technology [17] by inserting ferromagnetic poles between the magnets generates higher peak field, since the poles concentrate the magnetic flux which increases the on-axis induction of the magnets. The poles material is also an important parameter that affect the peak field. In general, iron enhances the field generated by a pure magnet wiggler, but Vanadium Permendur provides even higher field. Therefore, HPM technology with $Nd_2Fe_{14}B$ magnets poles made of Vanadium Permendur provides a solution to achieve a high field wiggler. The magnetic field can be tuned by adjusting the wiggler gap.

TABLE I: Fit coefficients a, b and c defining the peak field as a function of the ratio gap/λ_0 for the different kinds of planar wigglers [9].

case	description	a	b	c	gap range (mm)
A	PPM planar vertical field	2.067	-3.24	0	$0.1 < g/\lambda_0 < 1$
B	PPM planar horizontal field	2.4	-5.69	1.46	$0.1 < g/\lambda_0 < 1$
C	PPM helical field	1.614	-4.67	0.62	$0.1 < g/\lambda_0 < 1$
D	hybrid with vanadium permandur	3.694	-5.068	1.52	$0.1 < g/\lambda_0 < 1$
E	hybrid with iron	3.381	-4.73	1.198	$0.1 < g/\lambda_0 < 1$
F	superconducting planar (gap=12 mm)	12.42	-4.79	0.385	$12 < \lambda_0 <48$
G	superconducting planar (gap=8 mm)	11.73	-5.52	0.856	$8 < \lambda_0 < 32$
H	electromagnetic planar (gap=12 mm)	1.807	-14.3	20.316	$40 < \lambda_0 < 200$

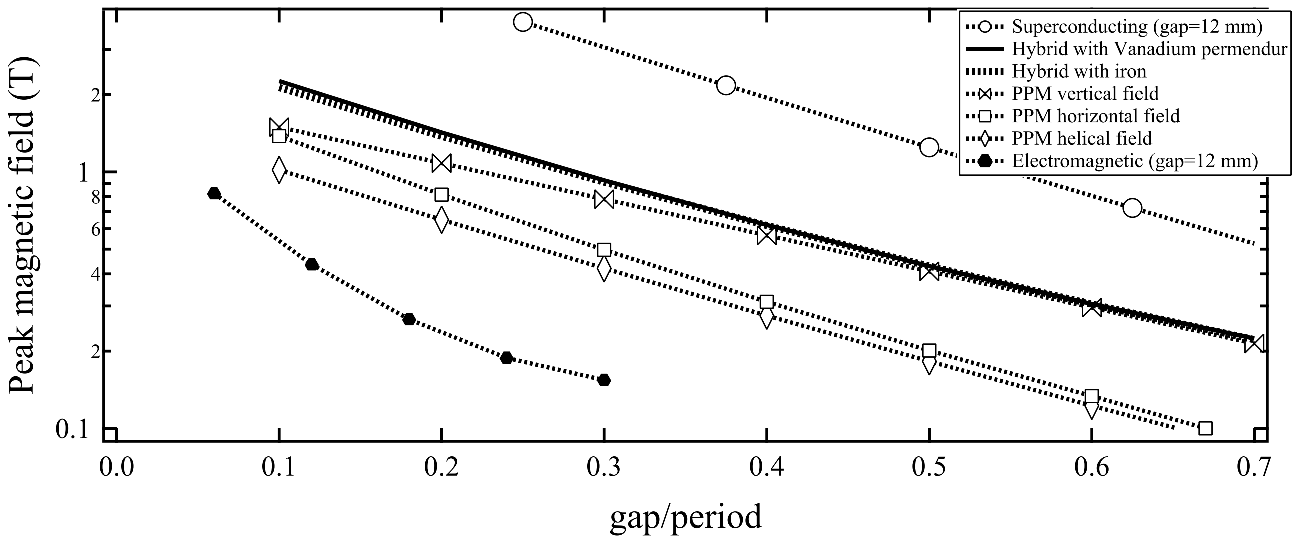

FIG. 3: Peak magnetic field as a function of the gap to period ratio (g/λ_0) for different wiggler technologies.

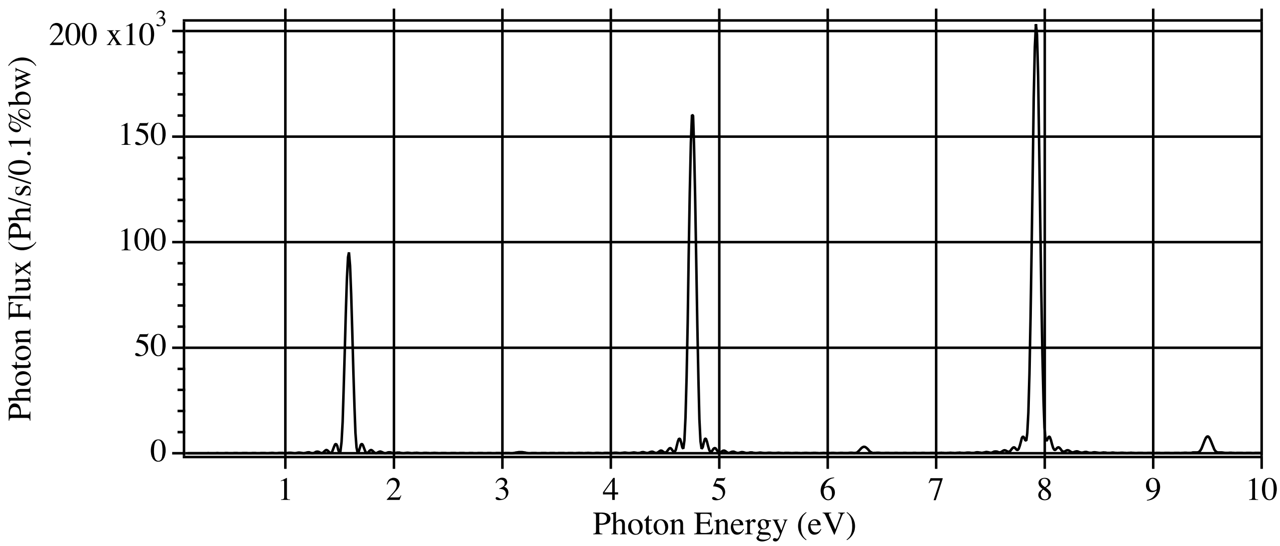

FIG. 4: Photon flux of the first proposed wiggler ($\lambda_0 = 164$ mm) in the undulator regime calculated by SRW at 10 m from the source through an aperture of $0.1 \times 0.1\ mm^2$. The wiggler is set at gap 16.7 mm. The magnetic field B=1.52 T. The electron beam parameters are: $E = 2.75$ GeV, $I = 500$ mA, $\beta_x = 4.6$ m, $\beta_z = 2.2$ m, $\epsilon_x = 3.9$ nm.rad, $\epsilon_z = 39$ pm.rad, $\sigma_e = 0.1\%$.

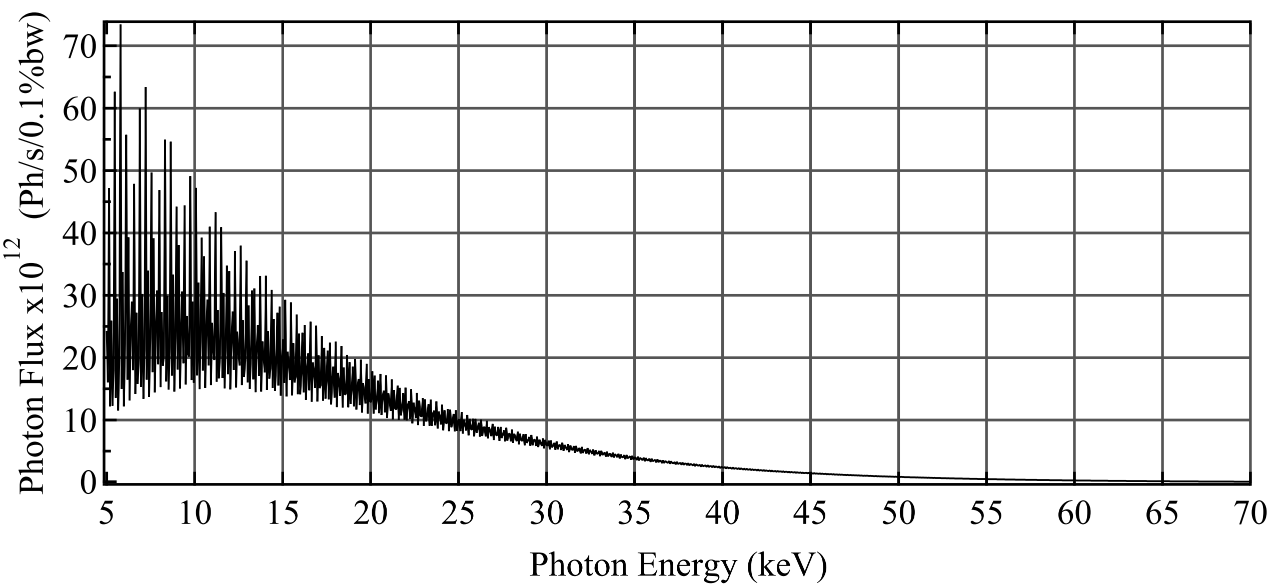

FIG. 5: Photon flux of the first proposed wiggler ($\lambda_0 = 164$ mm) in the wiggler regime calculated by SRW at 10 m from the source through an aperture of 0.1×0.1 mm^2. The wiggler is set at gap 14.7 mm. The field B=1.65 T. The electron beam parameters are: $E = 2.739$ GeV, $I = 500$ mA, $\beta_x = 4.6$ m, $\beta_z = 2.2$ m, $\epsilon_x = 3.9$ nm.rad, $\epsilon_z = 39$ pm.rad, $\sigma_e = 0.1\%$.

Here we give two proposals of insertion devices that can operate both in the undulator and the wiggler regimes and can be installed in a third generation light source of medium electron energy of 2.75 GeV. The gap to period ratio were optimized in accordence with [9]. Table II summarisez the main parameters of both proposals.

First proposal

The first proposal is HPM wiggler made of $Nd_2Fe_{14}B$ magnets and Vanadium Permendur poles. It is 164 mm period length and optimized at a gap of 14.7 mm (B=1.65 T) in the wiggler regime and at 16.7 mm (B=1.52 T) in the undulator regime. This wiggler was studied and installed at SOLEIL [19]. The photon flux emitted by the proposed wiggler is performed using SRW (Synchrotron Radiation Workshop) [20] over a low energy range (1-17 eV) at a gap of 16.7 mm. In addition to simulation over a higher energy range (5-70 keV) for the wiggler set at a gap of 14.7 mm.

Fig. 4 shows the radiation spectrum of the wiggler at gap 16.7 mm collected through an aperture of 0.1×0.1 mm^2 located at 10 m from the source. The spectrum is composed of clear and distinct harmonics in the form of narrow spectral lines, this is called the undulator regime.

Fig. 5 shows the radiation spectrum of the wiggler set at gap 14.7 mm through an aperture of 0.1×0.1 mm^2 located at 10 m from the source. It is noticed that the wiggler emits radiation in the undulator regime over the energy range (5-35 keV), since the spectrum is composed of distinct harmonics. Beyond 35 keV, the harmonics become closer and overlap. Therefore, the spectrum becomes smoother and the wiggler emits radiation in the wiggler regime.

Second proposal

The second proposal is also HPM wiggler made of $Nd_2Fe_{14}B$ magnets and Vanadium Permendur poles. However, in order to respect the condition $0.1 < g/\lambda_0 < 1$, it is 98 mm period length and optimized at a gap of 14.7 mm (B=1.78 T) in the wiggler regime and at 16.7 mm (B=1.63 T) in the undulator regime. The photon flux emitted by the proposed wiggler is performed using SRW over a low energy range (1-17 eV) at a gap of 16.7 mm. In addition to simulation over a higher energy range (5-70 keV) for the wiggler set at a gap of 14.7 mm.

Fig. 6 shows the radiation spectrum of the wiggler at gap 16.7 mm collected through an aperture of 0.1×0.1 mm^2 located at 10 m from the source. The wiggler emits radiation in the undulator regime at low resonance energy. The spectrum is composed of a series of distinct harmonics.

Fig. 7 shows the radiation spectrum of the wiggler at gap 16.7 mm collected through an aperture of 0.1×0.1 mm^2 located at 10 m from the source. The wiggler emits radiation in the wiggler regime in high energy range that spans from 5-70 keV. Here, the harmonics overlap and the spectrum become smooth.

TABLE II: Main parameters of proposal 1 and proposal 2

	Proposal 1 (λ_0=164 mm)		Proposal 2 (λ_0=98 mm)	
gap (mm)	$g = 14.7$	$g = 16.7$	$g = 14.7$	$g = 16.7$
B (T)	1.65	1.52	1.78	1.63
g/λ_0	0.09	0.101	0.15	0.17

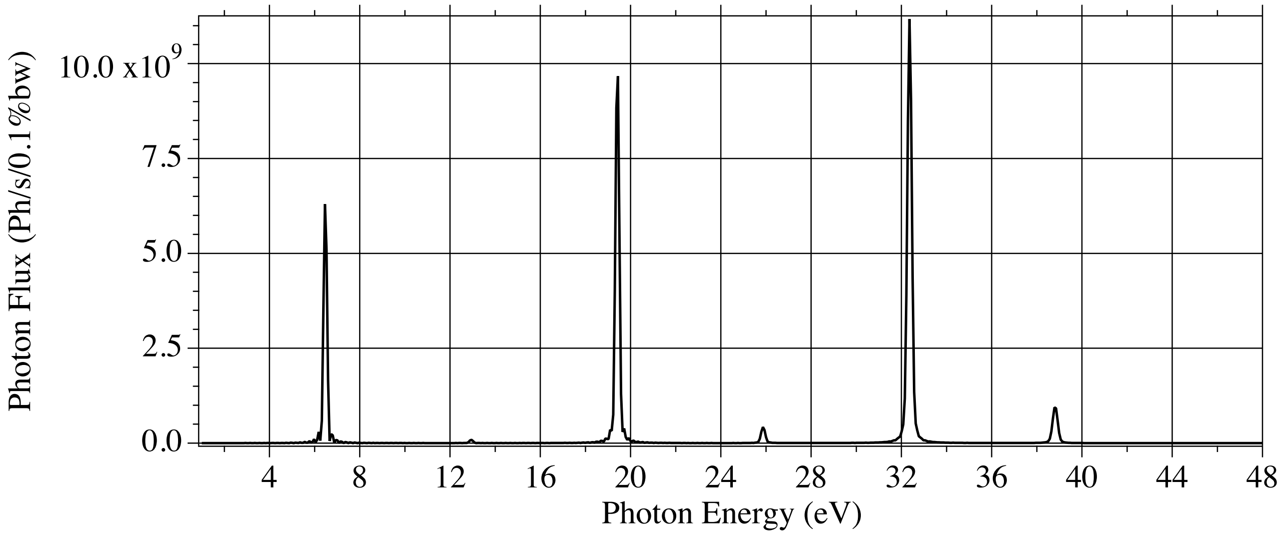

FIG. 6: Photon flux of the first proposed wiggler ($\lambda_0 = 98$ mm) in the undulator regime calculated by SRW at 10 m from the source through an aperture of 0.1×0.1 mm^2. The wiggler is set at gap 16.7 mm. The magnetic field B=1.63 T. The electron beam parameters are: $E = 2.739$ GeV, $I = 500$ mA, $\beta_x = 4.6$ m, $\beta_z = 2.2$ m, $\epsilon_x = 3.9$ nm.rad, $\epsilon_z = 39$ pm.rad, $\sigma_e = 0.1\%$.

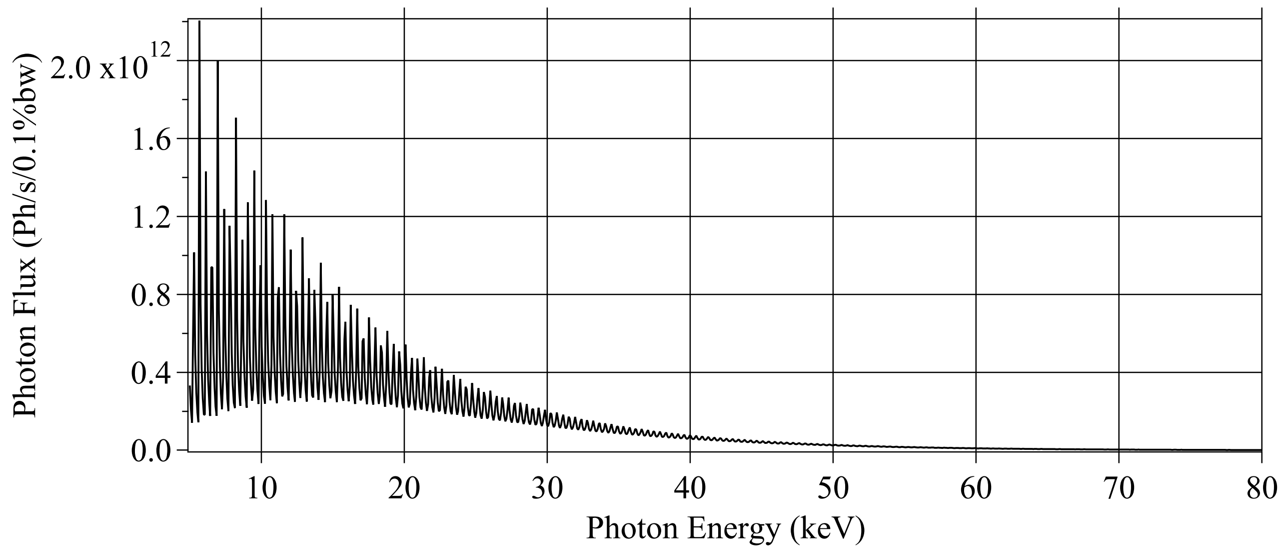

FIG. 7: Photon flux of the first proposed wiggler ($\lambda_0 = 98$ mm) in the wiggler regme calculated by SRW at 10 m from the source through an aperture of 0.1×0.1 mm^2. The wiggler is set at gap 14.7 mm. The magnetic field B=1.78 T. The electron beam parameters are: $E = 2.739$ GeV, $I = 500$ mA, $\beta_x = 4.6$ m, $\beta_z = 2.2$ m, $\epsilon_x = 3.9$ nm.rad, $\epsilon_z = 39$ pm.rad, $\sigma_e = 0.1\%$.

Conclusion

The proposed insertion devices are based on HPM technology and respect the condition of the gap to period ratio $0.1 < g/\lambda_0 < 1$. Both proposals provide high field wigglers and can operate both in the wiggler and in the undulator regimes. This provides an original and cost effective solution, since it can serve two independent beamlines for different scientific applications. The radiation regime can be adjusted by selecting the proper gap to select the covered energy range. This gives a margin of flexibility for the mechanical constrains on the minimum allowed gap in synchrotrons. The big advantage is that it provides a range period length for a wiggler designer. The first proposal provides 10^5 more flux in the undulator regime and 10 times more flux in the wiggler regime.

Ethics approval and consent to participate
The authors confirm that they respect the publication ethics and that they consent the publication of their work.

Consent for publication
The authors consent the publication of this work.

Availability of data and materials
Data is available upon the request

Funding
The license of the software used in the analysis of this work was funded by the French Consulate in Jerusalem.

Author's contribution
The results presented here are mainly based on H. Abualrob original idea and analysis of A. Bassalat, both authors produced the original draft.

Conflicts of interest
All authors declare that they have no conflicts of interest

Acknowledgments Authors would like to acknowledge the French Consulate in Jerusalem for their support.

References

[1] S. Krinsky, "Physics and technology challenges of ultra low emittance synchrotron light sources," in *Conference Record of the 1991 IEEE Particle Accelerator Conference*, pp. 11–15, IEEE, 1991.

[2] A. Nadji, P. Brunelle, M. Couprie, J. Denard, J. Filhol, J. Lamarre, P. Lebasque, A. Loulergue, P. Marchand, R. Nagaoka, *et al.*, "Operation and performance upgrade of the soleil storage ring," in *this conference*, 2011.

[3] S. Leemann, Å. Andersson, M. Eriksson, L.-J. Lindgren, E. Wallén, J. Bengtsson, and A. Streun, "Beam dynamics and expected performance of sweden's new storage-ring light source: Max iv," *Physical review special topics-Accelerators and beams*, vol. 12, no. 12, p. 120701, 2009.

[4] D. Einfeld, S. Hasnain, Z. Sayers, H. Schopper, and H. Winick, "Sesame, a third generation synchrotron light source for the middle east region," *Radiation physics and chemistry*, vol. 71, no. 3-4, pp. 693–700, 2004.

[5] V. L. Ginsburg, "Radiation of microwaves and their absorption in air," *Acad. Sci. U.R.S.S. Ser. Phys.*, vol. 9, no. 2, p. 165, 1947.

[6] H. Motz, "Applications of the radiation from fast electron beams," *Journal of Applied Physics*, vol. 22, no. 5, pp. 527–535, 1951.

[7] M. Korostelev, *Determination of the Absolute Luminosity at the LHC.* PhD thesis, CERN, Geneva, 2006.

[8] K. Halbach, "Physical and optical properties of rare earth cobalt magnets," *Nuclear Instruments and Methods in Physics Research*, vol. 187, no. 1, pp. 109–117, 1981.

[9] P. Elleaume, J. Chavanne, and B. Faatz, "Design considerations for a 1 å sase undulator," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 455, no. 3, pp. 503–523, 2000.

[10] M. Grioni, C. Lamberti, and A. San Miguel, "Applications of synchrotron radiation," *Séminaires Rhodanien de Physique. Editions Frontières, France,*, 1999.

[11] H. Onuki and P. Elleaume, *Undulators, wigglers and their applications.* CRC Press, 2002.

[12] A. Batrakov, F. Briquez, O. Chubar, I. Churkin, M.-E. Couprie, A. Dael, I. Ilyin, Y. Kolokolnikov, G. Roux, E. Rouvinski, *et al.*, "Magnetic design and manufacture of elliptical undulators hu256," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 575, no. 1-2, pp. 29–32, 2007.

[13] Y. Ivanyushenkov, M. Abliz, C. Doose, J. Fuerst, Q. Hasse, M. Kasa, V. Lev, N. Mezentsev, V. Syrovatin, E. Trakhtenberg, *et al.*, "Development of a superconducting undulator for the aps," in *Journal of Physics: Conference Series*, vol. 425, p. 032007, IOP Publishing, 2013.

[14] M. Fedurin, G. Kulipanov, N. Mezentsev, and V. Shkaruba, "Superconducting high-field three-pole wigglers at budker inp," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 448, no. 1-2, pp. 51–58, 2000.

[15] K. Strnat, "Current problems and trends in permanent magnet materials," in *AIP Conference Proceedings*, vol. 5, pp. 1047–1066, American Institute of Physics, 1972.

[16] M. Sagawa, S. Fujimura, N. Togawa, H. Yamamoto, and Y. Matsuura, "New material for permanent magnets on a base of nd and fe," *Journal of Applied Physics*, vol. 55, no. 6, pp. 2083–2087, 1984.

[17] G. Brown, K. Halbach, J. Harris, and H. Winick, "Wiggler and undulator magnets—a review," *Nuclear Instruments and Methods in Physics Research*, vol. 208, no. 1-3, pp. 65–77, 1983.

[18] T. Bizen, T. Tanaka, Y. Asano, D. Kim, J. Bak, H. Lee, and H. Kitamura, "Demagnetization of undulator magnets irradiated high energy electrons," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 467, pp. 185–189, 2001.

[19] O. Marcouillé, H. Abualrob, P. Brunelle, L. Chapuis, M.-E. Couprie, T. Elajjouri, M. Labat, J.-L. Marlats, F. Marteau, A. Mary, *et al.*, "W164: A wiggler dedicated to the puma beamline and the femtoslicing project at soleil," in *5th Int. Particle Accelerator Conf.(IPAC'14), Dresden, Germany, June 15-20, 2014*, pp. 1998–2000, JACOW Publishing, Geneva, Switzerland, 2014.

[20] O. Chubar and P. Elleaume, "Accurate and efficient computation of synchrotron radiation in the near field region," in *Proceedings of EPAC98*, (Stockholm, Sweden), pp. 1177–1179, 1998.

[21] M. Korostelev, *Optics design and performance of an ultra-low emittance damping ring for the Compact Linear Collider.* PhD thesis, Verlag nicht ermittelbar, 2006.