Review of Insertions in Synchrotron Light Sources

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1. INTRODUCTION

The radiation emitted by charged particles. moving in accelerating fields was, initially, considered a limiting effect for the particles final energy. The transition to the present day status, where synchrotrons and storage rings are built and designed to generate synchrotron radiation, was slow in coming. Bending magnets were the first sources of syncrotron radiation .With the parallel development of electron linear accelerators in the late 40's and early 50's, in 1947 Ginzburg suggested [1] the study the radiation from relativistic particles accelerated by periodic magnetic structures, with the goal of obtaining quasi-monochromatic short-wavelength radiation. The first observation and analysis of the so-called "undulator radiation" was published in 1951 by Motz [2] who utilized a 100 MeV electron beam passing through a permanent-magnet undulator with a period of 4.0 cm and a peak field of about 5.8 kG, yielding a spectrum peaked at about 33000 Å .

In a workshop held at Stanford in 1977 [3], the concept of "insertion devices" for storage rings was developed. The first wiggler magnet constructed expressely for Synchrotron-radiation research was commissioned in 1978 [4]. In this paper the main features of insertion devices are summarized, also in the framework of the synchrotron radiation properties. The structure of the paper is described in the following.

Section 2. is devoted to the description of the main features of the different sources of synchrotron radiation, commonly defined Insertion Devices (IDs), in connection with the emitted radiation spectral characteristics. In section 3. the technological aspects of IDs are summarized.

2. INSERTION DEVICES (IDs) FEATURES

2.1 *Spectral Properties From IDs*

ID is any magnetic device producing a transvers acceleration on the electron beam enhancing, with respect the case of the bending magnet, the radiated power or some specific characteristic of the emitted radiation.

Furthermore IDs are used for different purposes; the first ID on storage rings was the so called Robinson Wiggler [5] designed, not as a radiation source, but to control the emittance of the stored beam. A further example is the production of circularly polarized photons from Helical undulators, in order to measure electron or positron beam polarization in storage rings, as in the experiment realized on VEPP-2M at Novosibirsk [6]

The spectral structure of the emitted radiation can be a first criterion to clarify the common classification of the conventional IDs in Undulator Magnets (UM), wigglers and Frequency Shifters (FS). A second criterion regards the polarization properties of the emitted radiation. Most of the uncoventional IDs are devoted to obtain circularly or elliptically polarized radiation.

The spectral flux per unit solid angle emitted by relativistic electrons moving in bending magnets can be espressed in terms of modified Bessel functions. In practical units (photons s^{-1} mr^{-1} (0.1% banwidth)$^{-1}$) such a quantity writes:

$$dF/d\Omega = 1.33\times10^{13}\,E^2(\mathrm{GeV})\,I(A)\,x^2\,K^2_{2/3}(x/2)$$

where $x=\varepsilon/\varepsilon_c$ and ε_c is the critical photon energy

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

On the other hand the same quantity relevant to a magnetic device in which the on-axis magnetic field exhibit a N periods sinusoidal behaviour and in which the maximum angle of the electron trajectory with respect the axis is of the same order of the emission angle, reads (n refers to the order of the harmonic):

$$\frac{dF^n}{d\Omega} = 1.74\times10^{14}\,NE^2(\mathrm{GeV})\,I(A)\,B^2(x)\;\frac{\sin^2(N\pi\Delta\nu_n)}{(N\pi\Delta\nu_n)^2}$$

$$B(x) = 4\,(x/k)\,(J_{(n-1)/2}(x)-J_{(n+1)/2}(x))\;;$$

$$x=n\,(k/2)^2/(1+k^2/2);\qquad \Delta\nu_n = n-\varepsilon/\varepsilon_1$$

ε is the photon energy, a practical formula for ε_1 is given later.

This device is usually called Undulator and the radiation emitted by electrons travelling through its magnetic field exhibit a well defined harmonic structure as shown in Fig.1 .

The dimensionless k parameter is related to the UM characteristics:

$$k = 0.934\,B_0(T)\,\lambda_u(\mathrm{cm})$$

where B_0 is the magnetic field amplitude and λ_u the ID period. This is related to the harmonic contents of

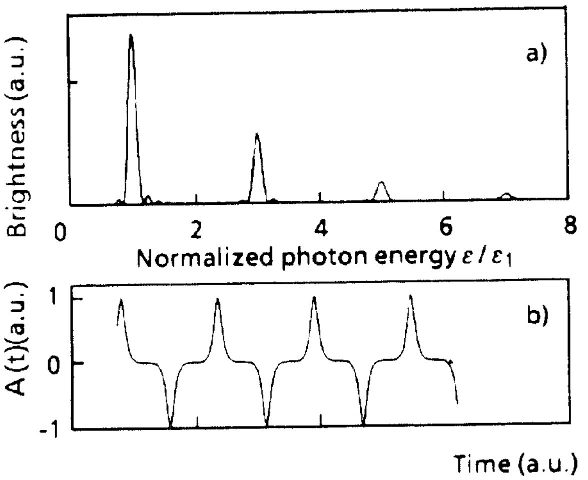

Fig. 1 - Brightness in the forward direction for an undulator with k = 0.7 (a), in comparison with the potential vector in time domain (b)

the trajectory as a function of the observer time. The spectrum is the result of the interferential pattern of all the emitting centers.

Since the emission angle is of the order of $1/\gamma$, and the average e.b. angle of the order of k/γ, for small k values all the trajectorie can be seen by an observer on the ID axis and the spectrum is the result of the interferential pattern of all the emitting centers. Increasing k the trajectory shape for each period is more and more symilar to the trajectory of a bending magnet as seen in the frame of the observer, on the other hand only a small part of the trajectory for each period gives rise to synchrotron emission in the observer direction, the emission in each period looses the correlation with each others and the final result is that the relevant brightness can be regarded as the incoherent sum of N bending magnets. The difference between UMs and Wigglers is essentially related to the larger k values of the latter. As an example in Fig.2 an intermediate case, corresponding to k = 3 is shown.

The trajectory in the transverse plane with respect to the direction of motion is described by the following expressions [7]:

$$\frac{dx^2}{ds^8} = -2\left(\frac{\pi k}{\gamma\lambda_u}\right)^2 h_x x; \quad \frac{dy^2}{ds^8} = -2\left(\frac{\pi k}{\gamma\lambda_u}\right)^2 h_y y$$

in which i) $h_x = h_y$ for helical undulator;
ii) $h_x = \delta$, $h_y = 2-\delta$ for linear undulator;
where δ is the so called sextupolar term.

The on-axis first harmonic photon energy for an UM is given by:

$$\varepsilon_1(\mathrm{keV}) = 0.65\,E^2(\mathrm{GeV})(\lambda_u(\mathrm{cm})/(1+k^2/2))$$

while for a Wiggler is the same as for bending magnets. The so called frequency shifter is a few periods (often only one) magnetic device with a very high magnetic field used to shift the spectrum in the region of shorter wavelengths.

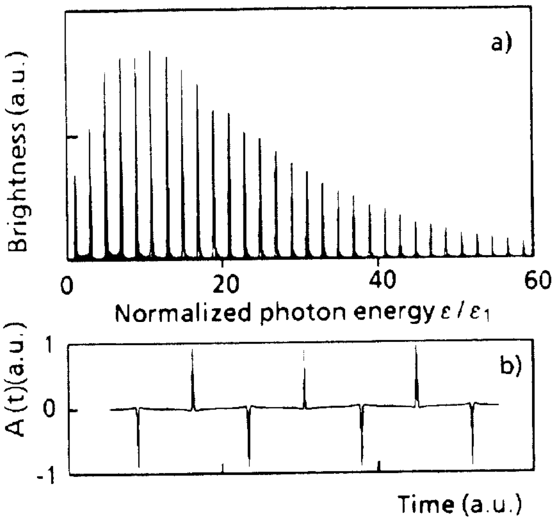

Fig. 2 - Same as Fig. 1 for k = 3

2.2 Polarization Properties

The state of polarization of the radiation emitted by a single electron travelling through an undulator is completely defined by the two components of $\mathbf{A}(\omega)$ in the observed direction, defined by the versor $\mathbf{n}$. $\mathbf{A}(\omega)$ stands for the Fourier transform of the vector potential of the radiated field [8]. A well known rappresentation of the state of polarization is given by the three components of the Stokes vector [9].

A different useful rappresentation for an electron beam with emittances that can give a direct information of the degree of different states of polarization of the radiation detected through a finite slit is described in ref. [10]. This method uses threedecomposition of $\mathbf{n}$ in orthogonal vectors:$(\mathbf{u}_x,\mathbf{u}_y)$, $(\mathbf{u}_R,\mathbf{u}_L)$, $(\mathbf{u}_{\pi/4},\mathbf{u}_{3\pi/4})$, where :

$$\begin{cases} \mathbf{u}_R = \frac{1}{\sqrt{2}}(u_y + i\,u_x); \\ \mathbf{u}_L = \frac{1}{\sqrt{2}}(u_y + i\,u_x); \end{cases} \begin{cases} \mathbf{u}_{\pi/4} = \frac{1}{\sqrt{2}}(u_y + u_x) \\ \mathbf{u}_{3\pi/4} = \frac{1}{\sqrt{2}}(u_y - u_x) \end{cases}$$

For each basis of decomposition the rate of polarization is defined as the ratio between the difference of intensity along the two orthogonal directions and the total one.

The sum of the three polarization rates plus the unpolarized rate P_d is equal to one:

$$1 = P_x^2 + P_{\pi/4}^2 + P_r^2 + P_d^2$$

As to the polarization properties of the emitted radiation UMs can be devided in two main classes : linear and helical.

Electrons moving through an ideal Linear UM experience a vertical component of the magnetic field sinusoidally varying along the UM axis. The radiation emitted by the electrons is linearly polarized.

In a Helical undulator both vertical and radial component of the on-axis magnetic field follow a sinusoidal behaviour and electrons travelling through the UM move along helical trajectories. In this case the emitted radiation is circularly polarized. Other unconventional devices are utilized in order to obtain circularly or elliptically polarized radiation using planar permanent magnet geometries. Some of that are able to control the degree of polarization of the emitted radiation.

In the following section the different technological solutions are described.

3. ID TECHNOLOGY

In this section various aspects of IDs design and manufacturing are described: different possibilities to generate the ID periodic magnetic field as well as special ID proposed designs are summarized. In order to minimaze the influence of IDs on storage rings and to optimize the radiation properties, a specific attention to the optimization of magnetic field is needed, thus measurement techniques and optimization techniques are carefully described.

3.1 ID magnetic field generation

There are different possibilities to generate a periodic magnetic field for an ID:

1) Electromagnetic ID - Initially undulators and wigglers were realized using iron poles surrounded by coils. This solution makes problematic the reduction of the magnet period or the increasing of the current density in the coils. There are three different kinds of difficulties: the cooling, the manufacturing of small coils, the required electrical power.

2) Pulsed electromagnetic ID - Short period high field undulators can be realized using iron-free pulsed coils in both linear and helical configurations. Such a solution is convenient in the case of FEL operating with low energy accelerators (Linac or Microtrons) and has been succesfully exploited in ref. [11].

3) Superconducting ID - This solution solves the problems affecting the electromagnetic IDs but at higher costs and technological difficulties. The first free electron laser experiment was realized in Stanford using a superconducting undulator [12].

4) Permanent magnets ID - UMs and Wigglers can be realized using Permanent Magnet materials (PM) instead of coils to generate a sinusoidal on axis magnetic field.

As to this last point two different solutions are usually considered namely pure and hybrid configurations. Pure UM uses PM blocks only, generally arranged in the so called Halbach configuration [13] as it is shown in Fig.3, where it is also indicated the behaviour of the on axis magnetic field. In hybrid UM, PM blocks as well as coils induce magnetic flux in iron poles (Fig.4) In this second case it is necessary to shunt the magnetic flux induced by the iron at the ends of the UM. The first and the last half periods are therefore anomalous with respect to the others. The convenience of pure or hybrid choice must be analyzed for any specific applications but in any cases it is strictly related to the range of variations of the ratio between the UM period and the working gaps.

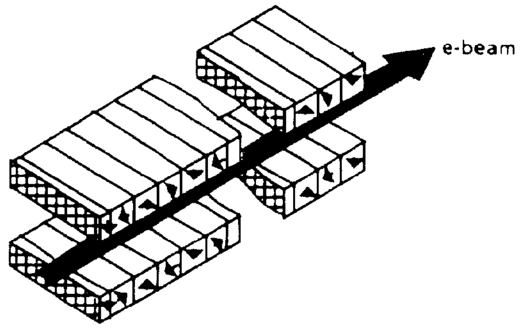

Fig. 3 - Pure permanent-magnet ID in the so called Halbarck configuration

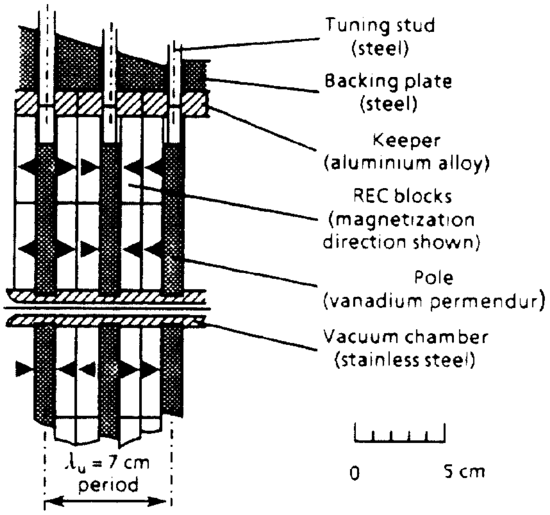

Fig. 4 - Hybrid permanent-magnet ID cross-section (from Ref. [13])

3.2 ID special design

Many different ID geometries have been proposed, some of them use planar PM arrangements to obtain circularly polarized radiation. As to the mechanism to get polarized radiation IDs can be classified in sources of helical, or more generally elliptical, magnetic fields, asymmetric wigglers and crossed undulators. Many different magnet dispositions have been proposed, some of them, belonging to the first group,have already been constructed .

- The elliptical Wiggler [14] consists of a conventional vertical field as in a linear Wiggler to which a small horizontal field of identical periodicity has been added in such a way that the transverse electron trajectory is a flat ellipse (Fig.5). This device allows a controll of the polarization varing the magnetic field amplitudes.

- The so called planar/helical UM geometry include a wide range of different PM blocks arrangements as proposed by many authors [15]. As an example Fig. 6 shown the device designed at ESRF in Grenoble.
- Asymmetric undulators were proposed and built at ESRF [16] and on DORIS III at DESY in Hamburg [17]. The magnetic structure and the magnetic field produced by this ID is shown in Fig.7.
- A Crossed undulator [18] consist of a pair of linear UM oriented at right angles to each others separated by a drift section (see Fig. 8). The amplitude of the radiation is a linear superposition of two parts, one linearly polarized along the radial direction and another along the vertical one. Crossed UM has been planned on ESRF, on the Daresbury DAPS and was recently tested on Bessy [19] in Berlin.

Different magnetic geometries have been proposed and built for the wide range of application of IDs. Some of them are briefly summarized in the following.

The use of tunable phase undulators has been recently proposed in order to vary the peak magnetic field without changing the gap [20].

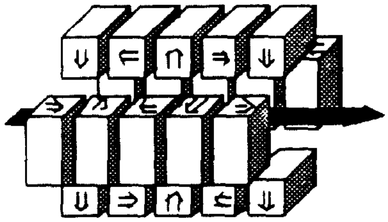

Fig. 5 - Schematic of an elliptical wiggler

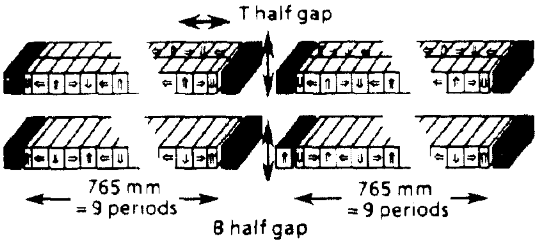

Fig. 6 - Magnetic design of the ESFR helical/linear undulator (from Ref. [15])

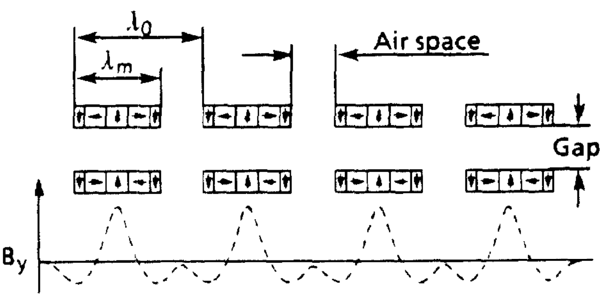

Fig. 7 - Asymmetric wiggler design and vertical mangetic field behaviour (from Ref. [17])

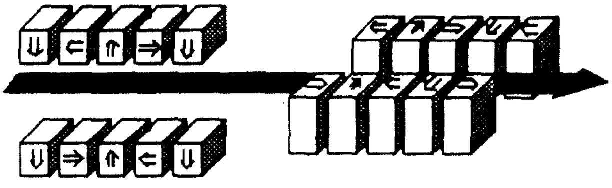

Fig. 8 - Schematic of a crossed undulator

Undulators in the so called optical klystron configuration have been used in ACO [21] and in Novosibirsk [22] for FEL operation. Such a configuration is used to enhance the small signal gain. Finally to enhance the photon energy both in storage ring and in single passage accelerators, the use of microundulators has been proposed [23].

3.3 Measurements and optimization

The concept of optimization of a Wiggler or of an Undulator is usually referred to

a) effect on the electron beam

b) spectral characteristics of the emitted radiation.

Both points are important for devices operating on storage rings, the second point is more important for devices designed for single passage FEL operation.

A wiggler insertion on a stright section of the storage ring can be considered optimized when the first and second longitudinal integrals of the magnetic field, given by the following expressions:

$$I_1(s) = \int_{-s}^{s} B_y(s')\,ds' \,; \quad I_2(s) = \int_{-s}^{s} ds' \int_{-s'}^{s'} B_y(s'')\,ds''$$

are minimized. Furthermore the minimization of sextupolar and in general of multipolar integrated contributions, should be considered. As an example Table 1 summarizes the IDs magnetic field performance specification for ELETTRA [24].

In the following a specific attention to the case of PM devices, in pure or hybrid configurations, is given. In an ideal pure PM configuration the integrals I_1 and

Tab. 1 : ELETTRA magnetic field performance specification (maximum) [24]

Field amplitude variation $\Delta B_0/B_0$ rms(total)	0.5% (+1%)
Horizontal field error (B_x/B_0) rms(total)	0.2% (+0.5%)
Dipole field integral errors	
- I_1	7.1μTm (h) 3.4μTm (v)
- I_2	54μTm^2 (h) 10μTm^2 (v)
Integrated multipole fields	
- quadrupole	0.008 T
-skew-quadrupole	0.01 T
- sextupole	0.5 T/m
- octupole	35.0 T/m^2

I_2 are authomatically zero while in actual cases the remanent field differences among the PM blocks can produce non zero contributions. In order to minimize the integral fields and to optimize the electron trajectories through the ID, for both pure and hybrid configurations, a carefully measurement of the single PM blocks is needed. Next subsection is devoted to the discussion of some different measurement methods for the PM blocks as well as for the evaluation of the integrals $I_1(s)$ and $I_2(s)$ and for the magnetic field behaviour through the ID.

- *Measuremets techniques* - Usually in the application of IDs it is necessary to satisfy very strong conditions on field homogeneity. To realize such conditions is necessary to measure the components of the magnetization vector with respect the nominal easy axis of the block in order to optimize the PM blocks assembling. The most direct method to measure the block magnetic characteristics is that of using a Hall probe to take a number of B-field point readings around the block [25]. Different methods use Helmholtz coils. An indirect measurement method of polarization angle displacement and relative magnetization strength, with respect to a reference block, uses a rotating holder surrounded by a coil. The magnet to be measured and the reference one are inserted in the holder with polarization moment parallel and antiparallel. The output waveform of the induced voltage in the coil is recorded and the amplitude and phase displacement, with respect a reference signal, are evaluated [26]. Hall probes mounted on benches are used to get information on the magnetic field behaviour along the ID. Integrated measurements on the whole ID are commonly obtained usign flipping coils.
- *Optimization techniques* - The first optimization of the magnetic field behaviour consists in the assembling criteria of the PM blocks. However to reach the desidered degree of homogeneity in the magnetic field and the required minimum values for the field integrals a further optimization is necessary. This is possible utilizing tuning studs, coils or the so called shimming technique. Tuning studs are utilized in hybrid configurations [13] and allow a relevant local correction of the magnetic field inhomogeneitis. A whole compensation of ID is usually not convenient because the correction is gap dependent. The shimming techique [15] costists in the use of thin plates of soft magnetic material (shims) which are placed on the surface of UM or wiggler. The shims can be used to modify the field integral and the local field independently. This technique is available for both pure as well as hybrid configurations and the compensation should be gap independent.

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