Insertion Devices for Synchrotron Radiation and Free Electron Laser

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Preface

Accelerated charged particles emit radiation. Albeit the work of Larmor (1897) and Lienard (1898), accomplished few years later the development of the Maxwell theory (1873), provided the theoretical foundations of this phenomenon, the first visual observation of what is now termed synchrotron radiation, dates back to about 50 years ago, with the first operations of the 70 MeV synchrotron of General Electric (G.E.).

It is interesting to note that, after the pioneering work of Lienard and Larmor, this topic was largely unnoticed and gave rise to a brief flurry of interest with the work of Schott (1907,1912), who published a detailed analysis including the angular and frequency distribution of the emitted radiation as well as the polarization properties. There are at least two reasons, which may explain the initial lack of interest for this type of effect and for its theoretical implications

1) since its observation requires ultrarelativistic charged particles, it was regarded as a curiosity rather than a really observable phenomenon,

2) The use of the physical concepts, related to the synchrotron radiation, within the context of the microscopic theory of atomic phenomena was readily discouraged by the developing quantum mechanics and by its success in explaining the observed spectra.

During the second world war the problem was reconsidered by the Russian scientists Iwanenko and Pomeranchuk (1944), who argued that radiation, emitted by particles moving on circular paths and the consequent energy loss, may pose a limit on the maximum energy attainable with a circular accelerator.

The monumental work of Schwinger provided the final rigorous settlement of the theory and explained why the first experimental attempts by Blewett, to detect synchrotron radiation, failed. Although Blewett measured the particle energy loss in the 100 MeV betatron of G.E. and found agreement with the theory, he looked for synchrotron radiation in the range of microwaves. The work of Schwinger pointed out that the spectrum is peaked at much higher frequencies and that the power emitted in the microwave region is negligible.

The subsequent discovery with the 70 MeV G.E. synchrotron occurred by chance rather then by systematic investigation.

Before going further, let as underline that even-though any charged particle looses energy in the form of electromagnetic radiation, synchrotron radiation is the radiation emitted by charged particles travelling on curved paths. In the case of high energy electrons moving in the magnetic field of Storage Rings, the emitted radiation is extremely intense on a wide range of wavelengths, extending from the infra-red to the soft and hard X-ray region of the spectrum.

The historical development we have sketched shows that science proceeds gradually. Synchrotron radiation became a mature subject with the development of the technology of high energy accelerators. Synchrotron radiation was initially viewed as a limiting factor to accelerate particles at higher energies with circular machines, now its peculiar features of wide band, high spectral fluxes, directionality etc., make it a unique tool of investigations for basic and applied studies in biology, chemistry, medicine, physics and in applications to technology such as X-ray litography, micromechanics, material characterization and so on.

Machines dedicated to the production of synchrotron radiation are widespread all over the world and are not restricted to the most technologically advanced countries. Many synchrotron radiation facilities are located or are going to be realized in emerging or less developed countries, where they are seen as a way to develop new technologies and new tools in basic research and in industrial applications.

Synchrotron radiation sources are essentially provided by Storage Rings, with dimensions ranging from few meters in circumference and operating at a few hundred MeV to devices up to 1500 meters in circumference and operating in the GeV region.

The historical development of synchrotron radiation sources has proceeded through three steps which are known as the three generations of synchrotron radiation sources.

a) First generation

The Storage Rings of this generation were originally built for high energy research. The synchrotron radiation programs started in a parasitic mode and have grown to the point where facility is partially or fully dedicated to synchrotron radiation research.

b) Second generation

The sources of this generation are designed specifically to produce synchrotron light. These rings are characterized by a large number of beam lines, which may serve many users. The first example of second generation synchrotron radiation source is the 380 MeV SOR ring at the university of Tokyo.

c) Third generation

The rings of this generation have lower emittance, many straight sections for insertions and are designed to provide spectral photon fluxes much larger than those of the second generation.

In 1976 it was experimentally demonstrated that stimulated synchrotron radiation, namely the Free Electron Laser (FEL), can be obtained. Since then, various FEL facilities have been designed and operated. These new facts have opened the possibility of using Storage Rings or Linacs to realize fourth generation devices. Such sources would provide improvements of several orders of magnitude in the spectral fluxes, with respect to the performances of the third generation rings.

The amount of scientific and technical literature on synchrotron radiation and relevant sources and facilities is immense, it is therefore natural to ask why a further book on synchrotron radiation and insertion devices?.

The Authors have spent most of their scientific lives, working on the theory of synchrotron radiation, on the theory of FEL, on the design of wigglers, of undulators and of transport lines for electrons in high energy accelerators (Linacs and Storage-Rings), have participated to the design of FEL and proposed new schemes for the generation of X-ray sources. They witnessed the birth of FEL, contributed to its theoretical and technological developments, and contributed to the theory of synchrotron radiation, by presenting a comprehensive treatment of the spectroscopic details of the radiation emitted by relativistic electrons moving in magnetic undulators with different configurations. The above quoted experience can be helpful to provide a book which may be useful if it will give the correct idea of what is synchrotron radiation, how is produced, how is exploited and why, how will compete and cohabit with FEL devices, what will be its future.

The goal sounds ambitious!

We believe that a book is useful when it can be used by pedestrians and by scientists already expert in the field. We have therefore designed the book in such a way that the experts may use it as reference manual. We have indeed collected the main results by using practical formulae which can also be used for design purposes. The pedestrians will find concise results which privilege the physical and technological aspects and avoid as much as possible the mathematical details.

During the years of our activity we had the privilege of working with distinguished scientists in the field of synchrotron and Free Electron Laser radiation. They shared with us their points of view and provided the cultural background which made possible the completion of this book. We owe them our gratitude. Among them it is our pleasure to mention drs. G.K. Voykov and L. Giannessi who collaborated with us on various topics relevant to synchrotron radiation and FEL theory and in particular developed important methods to use the synchrotron radiation as a diagnostic tool for the characteristics of the emitting beam. It is also a pleasure to express our sincere appreciation to the generous and constant assistance of Dr. P.L. Ottaviani. Most of the ideas contained in chapter III are the result of ten years of joint research between him and one of the Authors (G.D.).

We have already mentioned that the scientific literature on synchrotron radiation and related topics is enormous, therefore, at the end of each chapter, the reader is not addressed to specific contributions, but mainly to books and review articles. Doing so we are not making justice to each contributors and for this we sincerely apologize in advance.

This book does not cover all the details of synchrotron radiation theory, of FEL theory and of the design and manufacturing aspects of the devices most commonly used to produce synchrotron and FEL radiation, its lecture should be therefore complemented by that of other books and review articles which are listed below, along with the seminal papers mentioned in this preface.

1. J. Larmor, Phil. Mag. 44, 503 (1897).
2. A. Lienard, L Eclairage Electrique 16, 5 (1898).

3. G.A. Schott, Ann. Phys. 24, 635 (1907).
4. G.A. Schott, Electromagnetic radiation, Cambrige University Press. (1912).
5. D. Ivanenko and I. Pomeranchuk, Phys. Rev. 65, 343 (1944).
6. J. Schwinger, Phys. Rev. 70, 798 (1946).
7. J.P. Blewett, Phys. Rev. 69, 87 (1946).
8. F.R. Elder, R.V. Langmnir and H.C. Pollock, Phys. Rev. 74, 52 (1948).
9. J.D. Jackson, Classical Electrodynamics, Wiley, New York (1962).
10. A.A. Sokolov and I.M. Ternov, Synchrotron Radiation, Akademic-Verlag, Berlin (1968).
11. S. Krinsky, M. Perlman and R.E. Watson, Characteristics of Synchrotron Radiation and of its Sources, in Handbook of Synchrotron Radiation, ed. by E.E. Koch, North-Holland, Amsterdam (1983).
12. G.Dattoli and A.Renieri, Experimental and Theoretical aspects of Free Electron Lasers, in Laser Handbook, Vol. IV, ed. by M.L. Stitch and M.S. Bass, North-Holland, Amsterdam (1984).
13. K.J. Kim, Characteristic of Synchrotron Radiation, AIP Conference proceedings, p.565, 184, Vol 1, AIP, New York (1989).
14. J.C. Marshall, Free Electron Lasers, Mac Millan Publishing Co, New York (1985).
15. A. Hofmann, Theory of Synchrotron Radiation, SSRL ACD note (SLAC), (Sept. 1986).
16. A. Hofmann, Characteristic of Sychrotron Radiation, Proceedings of CAS, CERN 90-3 (1990).
17. R.Barbini, F.Ciocci, G.Dattoli, L.Giannessi and A.Torre, Spectral Properties of the Undulator Magnet Radiation: Analytical and Numerical Treatment, La Rivista del Nuovo Cimento 6, (1990).
18. P.Luchini and H.Motz, Undulators and Free Electron Lasers, Claredon Press, Oxford (1990).
19. C.A. Brau, Free Electron Lasers, Academic Press, Boston (1990).
20. G.Dattoli, A.Renieri and A.Torre, Lectures on the Free Electron Laser Theory and Related Topics, World Scientific, Singapore (1995).

Foreword

Synchrotron radiation (S.R.) is the energy lost by a charged particle moving with relativistic speed on curved trajectories.

In particular high energy electrons traversing the field of bending, undulator or wiggler magnets, produce intense laser-like radiation on a broad range of frequencies not accessible with other sources.

To produce S.R. it is necessary to have

a) high-energy electrons

b) a magnetic field which constraints the electrons on a curved path.

It is evident that the most natural candidate as source of S.R. is a Storage Ring ($\mathcal{SR}$). In this device electrons (or positrons) circulate on a closed orbit. It is fairly natural that radiation be lost when the electron curve in the Storage Ring bending magnets. However they can also be forced to radiate by inserting wigglers or undulators (Fig. 1) in the straight sections of the Storage Ring.

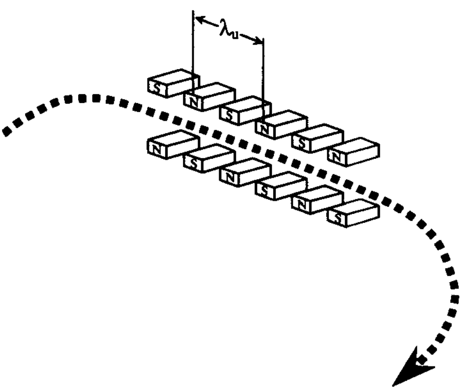

Figure 1 Undulator scheme

Wiggler and undulator magnets are the most commonly adopted insertion devices (ID) to produce S.R. . Since each one of these devices affects the electron motion in a different way, we can expect that the characteristics of the emitted radiation are not the same for any type of insertion.

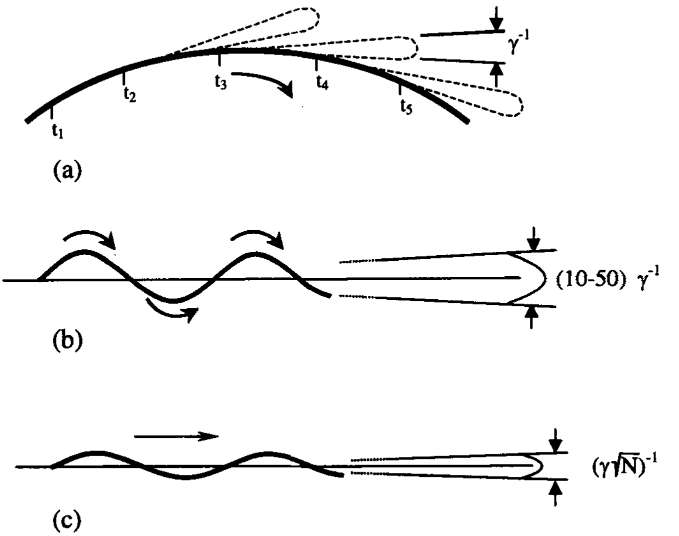

Figure 2 Schematic of emission characteristics for the three main types of synchrotron light sources: bending magnet (a), wiggler (b), undulator (c).

The bending magnets, or dipoles, bend the electron beam (e-beam) through short arcs, which close the orbit since add up to a total of 360 degrees. The electrons moving in bending magnets describe a circular orbit and produce a broad-band smooth spectrum.

Wigglers are essentially a sequence of bending magnets with alternate polarities. The emitted radiation has spectral characteristics analogous to those of bending magnets, with an intensity enhancement of a factor 2N, where 2N is the number of poles.

In the undulator the electrons propagate by executing smooth transverse oscillations, keeping into the emitted radiation cone in any point of the trajectory. As a result of the interference between radiation emitted from different points of the trajectory, the spectrum consists of a series of quasi-monochromatic peaks. The differences between the spectra of the three devices are, perhaps, better clarified by figs.2-4.

In the case of bending magnet (see fig. 2a), an observer placed on axis will receive a stream of photons by the radiating electron for a very short time, he will therefore measure a narrow electric field in the time domain, corresponding to a broad-band field in the frequency domain (see fig. 2b-c).

Being the wiggler an array of 2N bending magnets, the on axis observer will receive 2N distinct short time photon streams. The measured field will consist of a series of distinct sharp peaks in the time domain and of a broad-band spectrum, 2N time more intense than the single pole spectrum (see fig. ??a-c).

In the case of the undulator, the electrons do not execute large transverse oscillations. The on axis observer will receive an almost continuous signal in the time domain, in the frequency domain the spectrum is squeezed into a series of harmonics (see fig. 4a-c).

In the case of bending and wiggler magnets the spectrum is a smooth continuum characterized by the so called critical frequency

$$\varepsilon_c\,[KeV] = 0.665\ B\,[T]\ \ E^2\,[GeV] \tag{1}$$

one half of the spectrum is radiated below ε_c, one half above ε_c. In eq. (1) B is the on axis magnetic peak field generated by the poles of the device, expressed in *Tesla* ($10^4\,Gauss$) and E is the electron energy in GeV ($10^9\,eV$). To give an example for a 1-GeV Storage Ring with $1\,Tesla$ magnetic field, the critical frequency is $0.665\,KeV$. By recalling that the wavelength is related to the energy of the radiation emitted by the practical formula

$$\lambda\,[cm] = \frac{1.2399 \cdot 10^{-7}}{\varepsilon_c\,[KeV]} \tag{2}$$

we infer that one half of the spectrum is emitted above and below the UV region (see fig. 5).

As already remarked the undulator spectrum is provided by a series of nearly monochromatic peaks centered around (n is the order of the harmonics)

$$\varepsilon_n\,[KeV] = \frac{0.947\ n\ E^2\,[GeV]}{\lambda_u\,[cm]\ \ (1 + k^2/2)} \tag{3}$$

where λ_u is the undulator period (see fig.1) and k is the undulator strength, linked to the on axis magnetic peak field and period by

$$k = 0.9362\ B\,[T]\ \ \lambda_u\,[cm] \tag{4}$$

For $E = 1\ GeV$, $k = 1$ and $\lambda_u = 3\ cm$, we find that the first harmonic is radiated around $\varepsilon_1 \cong 0.21\ KeV$.

To give a further feeling on the numbers involved in, we note that the energy lost per machine turn by an electron in a bending magnet is

$$\delta E\,[KeV] = 26.6\ B\,[T]\ \ E^3\,[GeV] \tag{5a}$$

while the corresponding power, lost by a stored current, is

$$P_{S.R.}\,[KW] = I\,[A]\ \ \delta E\,[KeV] \tag{5b}$$

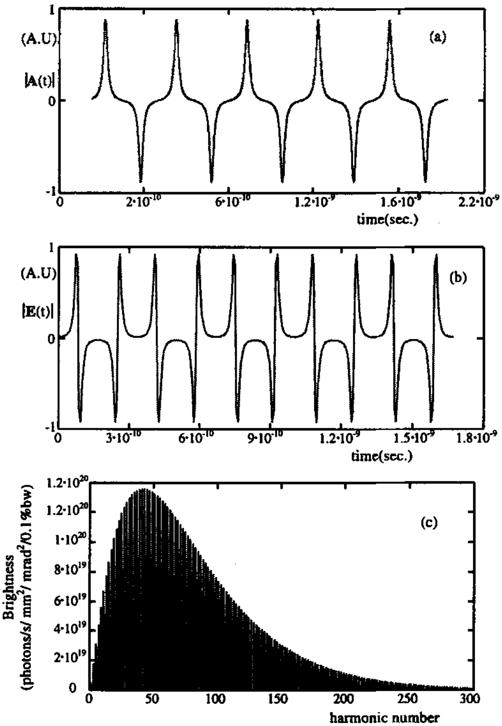

Figure 3 Characteristics of the e.m. radiation emitted in a wiggler with $\lambda_u = 10\,cm$ and strength parameter $k = 4.5$: (a) vector potential and (b) electric field modulus vs time, (c) brightness vs the harmonic number.

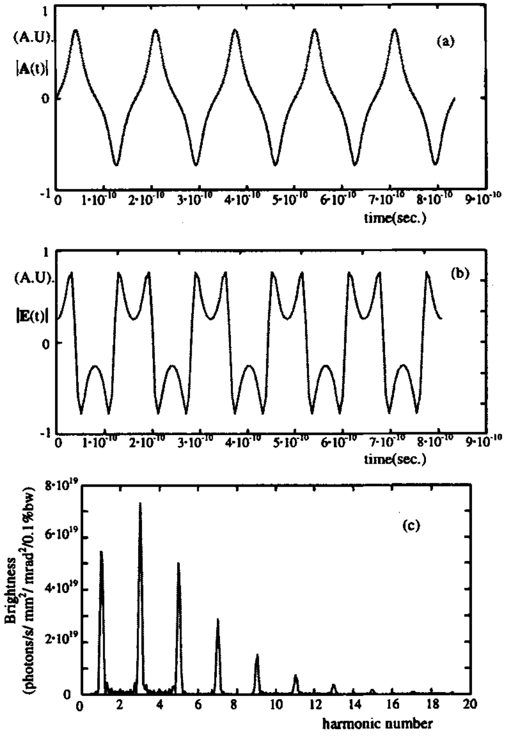

Figure 4 Characteristics of the e.m. radiation emitted in an undulator with $\lambda_u = 5\,cm$ and strength parameter $k = \sqrt{2}$: (a) vector potential and (b) electric field modulus vs time, (c) brightness vs the harmonic number.

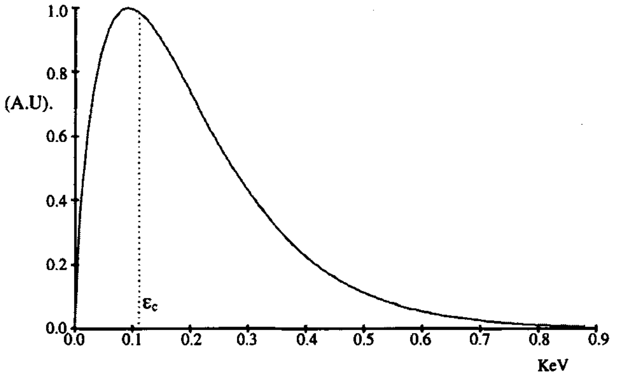

Figure 5 Synchrotron radiation spectrum

where I is the beam current expressed in Ampers.

According to eqs. (5a), the energy lost by a $1\,GeV$ electron in the field of $1\,Tesla$, is $26.6\,KeV$, and a stored current of $1\,A$ radiates $26.6\,KW$ per machine turn. Only a fraction of this power can be exploited for research purposes but all the lost power must be replaced by the Storage Ring accelerating system, to guarantee the stability of the device.

In the case of wigglers or undulators eq. (5a) should be replaced by

$$\delta E\,[KeV] = 0.633 \cdot E^2\,[GeV] \cdot \left\langle B^2\,[T] \right\rangle \cdot L\,[m] \tag{5c}$$

where $< B^2[T] >$ represents the average square value of the magnetic field of the device over its length L. The energy lost by one GeV electrons, moving in a $1\,m$ undulator with $< B^2 > \cong 1\,T^2$, is $0.633\,KeV$ and the corresponding power, radiated by a $1\,A$ beam, is $0.633\,KW$. The difference with the bending magnet case is that all the radiation emitted in the undulator or wiggler device can be delivered into the experimental stations.

We have mentioned at the beginning of these general remarks that S.R. exhibits laser- like properties. This is a very important point which should be clarified before entering into the main body of the book. In some experiments it is important that the sample receives a high photon flux, which is defined as

$$F = \#\ photons\ /\ \sec \cdot mrad \cdot \Delta\omega_B \tag{6a}$$

where $\Delta\omega_B$ is the unit bandwidth.

Other experiments demand for a very high brightness beam, this latter quantity being defined as

$$B = \# \ photons \ / \ \Delta\Omega \cdot S \cdot \Delta\omega_B \tag{6b}$$

where $\Delta\Omega$ is the unit solid angle and S is the unit source area.

Along with brightness, high coherent power is required. Coherence and brightness are strictly related to the transverse quality of the e-beam, namely to its transverse phase-space area. To smaller emittances correspond larger brightness The emittances are in turn determined by the structure of the transport system inside the ring. Emittances of about 100-200 *nmrad* are typical of second generation rings, insertion devices on these rings may produce photon beam with brightness 10^{16}- 10^{17} $(photons/sec/mm^2/mrad^2/0.1\%\Delta\omega_B)$. Third generation rings are designed to produce one order of magnitude lower emittances and photon beam with brightness up to 10^{19} $(photons/sec/mm^2/mrad^2/0.1\%\Delta\omega_B)$.

It is important to keep in mind that the properties of the emitted radiation depend on the characteristics of the radiating beam, which are in turn determined by the structure of the transport system, or more technically by the lattice. The analysis of insertion devices for S.R. cannot be viewed by itself, but as a part of a whole carefully integrated in the rest of the system. A part of this book will be, therefore, dedicated to the design of lattices and to their interplay with the characteristics of the emitted radiation. The design and construction of IDs usually concern a) the effects on the e-beam b) the spectral characteristics of the emitted radiation.

Both points are important for the optimization of the devices. The first, crucial point for devices operating in Storage Rings, will be discussed in chap. 3. A further important issue is linked to the characterization of the magnetic field of the device. Wigglers and undulators are most commonly realized by means of permanent magnet materials. The technological aspects relevant to the construction of these devices will be extensively discussed in the book as well as the methods relevant to the field measurement.

Free Electron Lasers (FEL) devices, have been independently developed since the last twenty years. In a FEL a beam of relativistic electrons, not necessarily from a Storage Ring, is injected into a magnetic undulator, which provides a transverse component to the electron motion, thus allowing the coupling of the beam with a copropagating TE wave, nearly resonant with one of the harmonics (normally the first) of the undulator spectrum. The coupling induces an energy modulation of the beam, which is followed by a density modulation and by a coherent emission, occurring when the density modulation is of the same order of the wave-length of the TE-wave.

In a FEL oscillator the emitted radiation, stored in an optical cavity, reinteracts with the e-beam and becomes amplified until gain saturation occurs. In fig. 6 we have reported the schematic layout of an ID in a Storage Ring. The laser optical cavity and the undulator are inserted on the straight section of the ring. The maximum attainable laser power is linked to the total power emitted in one machine turn via synchrotron radiation, namely

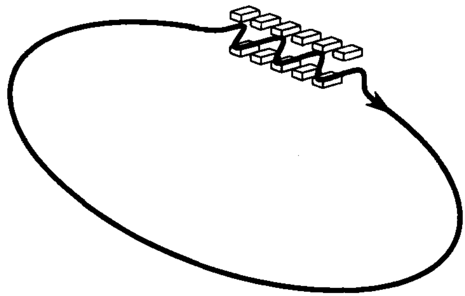

Figure 6 Schematic layout of an ID on a straight section of a Storage Ring.

$$P_L \cong P_{S.R.} \,/\, 2N$$

where N is the number of periods of the undulator.

Experiments requiring higher brightness, higher coherence, higher peak power are benefitting from the peculiar characteristics of a Storage Ring FEL.

We must, finally, underline that oscillator FELs are limited to the region in which mirrors to confine the produced radiation are available. We can safely assume a lower limit for wavelengths around 180 nm, i.e. not above VUV region (see fig. 5).

FELs operating in the X-region require a mirrorless configuration, known as SASE (self amplified spontaneous emission) which employes high current and high energy Linacs. In this case the output laser power is proportional to a fraction of the e-beam power and may reach power densities of the order of $10^5\, MW/cm^2$.

The preliminary remarks we have given, yield, perhaps, an idea of how the field of S.R. is close to a significant evolution and that the interplay with FEL may provide significant improvements and enlarge the number of possible applications.

This book contains a description of conventional $\mathcal{SR}$ insertion devices and includes some comments on FEL and on its use.

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