INSERTION DEVICES FOR THE PRODUCTION OF ELECTROMAGNETIC RADIATION

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Abstract

This is a brief overview of the various types of insertion devices (wigglers, undulators, Compton scatterers, free electron lasers,...) used on ultrarelativistic electron beams for the production of electromagnetic radiation from infrared to γ-rays, their description as optical sources, the spectrum of applications and some possible future lines of development.

Introduction.

Interaction of charged particle (usually electron) beams with electromagnetic (em) fields produces em radiation as the particles are accelerated.

Insertion devices (ID) are fields of a suitable shape in order to produce radiation with some desired characteristics, inserted in the straight section of an ultrarelativistic electron storage ring, or at the exit of a single-pass machine, as for ex. a linac.

They are used to produce radiation ("spontaneous" or (at longer wavelengths) "stimulated") in a range from γ rays to the far infrared; or in some cases for beam monitoring. They are usually periodic. Rather generally we can view the interaction producing the radiation as a nonlinear Compton effect, where the amount of nonlinearity is determined by the "deflection parameter" $\bar{K} = e\bar{B}\lambda_o/2\pi mc^2$ (λ_o em field period, $\bar{B}$ rms magnetic field). Ultrarelativistic electrons ($\gamma >> 1$) produce a shrinking of the emitted wavelength (at angle θ from the forward direction) with respect to λ_o (for the h-th harmonic):

$$\lambda = \frac{\lambda_o}{2\gamma^2 h(1+w/c)}(1+\bar{K}^2+\gamma^2\theta^2)$$

(where w is the velocity of the (counterpropagating) field, =0 for a static field)

Most devices now in use are based on static magnetic fields, as fields of one or several Tesla can easily be obtained, which are difficult to obtain with electrostatic fields (1 Tesla is equivalent to $3\cdot 10^8$ V/m) or with em waves (1 Tesla is equivalent to $2.4\cdot 10^8 W/mm^2$).

This short paper cannot be a tutorial or a review; it is a kind of index of subjects or a memorandum, with bibliographical references to a minimum number of papers, mainly reviews (without attempt to completeness or to a historical picture). Among general references are brief introductions [1,2], reviews [3-10], tutorials [11], conference proceedings [12,13].

Various types of ID.

Types of electron beams:

- beam in a straight section of a storage ring (high repetition rate, beam sensitive to perturbations as accumulated over the synchrotron damping time, very high energies obtainable).
- beam in a "bypass" in a storage ring (lower repetition rate, beam less sensitive to perturbations).
- beam at exit of machine (for ex. linac) (the beam can receive a strong perturbation or lose an appreciable part of energy (ex. tapered FEL). Low repetition rate. New low emittance cathodes have increased the interest in free electron lasers (FEL) based on linacs)[14].

Types of devices

- Wiggler.

A static magnetic field (permanent magnet, electromagnet or superconductor, from a fraction of Tesla to several T), periodic (not necessarily sinusoidal, possibly one period only ("wavelength shifter")) in which, at least in the part of the spectrum we are looking at, spectrum and angular distribution are smooth and similar to those from a uniform magnet (with intensity multiplied by 2N (N = number of periods)), and phase space distribution a bit smeared [15]. The right value of the deflection parameter K is a compromise between smooth spectrum and good phase space distribution [11].

- Undulator

A periodic (usually sinusoidal, sometimes helical) magnetic field (permanent magnets for shorter periods, electromagnets for longer ones) where interference between different peaks of the trajectory (for the same electron) is not destroyed by the contribution of electrons at random positions and angles and it is used to concentrate the radiation in a smaller solid angle and narrower bands. The same device can be a wiggler at short λ and an undulator on the first harmonics [11].

The spectral flux (number of photons/second/relative banwidth) can be expressed as:

$$\Phi = \alpha n N U_h(\bar{K})$$

, (with $\alpha \simeq 1/137$ fine structure constant, n = number of electrons/sec., N num. of periods, U_h a function of $\bar{K}$ only (or of λ/λ_1, with $\lambda_1 = \lambda_o/2\gamma^2$)). $U_1(\bar{K}) \simeq \bar{K}^2$ for $\bar{K} << 1$, $U_1(\bar{K}) \to 0.97$ for $\bar{K} \to \infty$.

For the distribution of this flux in phase space, we have two limiting cases:

. emittance-limited radiation: source size and divergence are equal to those of the electron beam: the radiation can be described as geometrical-optics rays.

. diffraction-limited radiation: it is spatially coherent as from a single electron (source size is $\sim (\lambda L)^{1/2}/2\pi$, angular aperture $\sim (\lambda/L)^{1/2}$, L = undulator length); relative banwidth $\Delta\lambda/\lambda \sim 1/N$.

- Laser undulators (Compton backscattering).

Very short periods ($0.1 \div 10\mu m$) can be obtained only with lasers. These have been used to produce 100-MeV polarised γ-rays [15]. Quantum recoil (or energy conservation) reduces the energy of the emitted photon: the emitted photon energy $\hbar\omega$, ($\bar{K} << 1$), is

$$\hbar\omega = 4\gamma^2\hbar\omega_o/(1+\gamma^2\theta^2+\frac{2\gamma\hbar\omega_o}{mc^2})$$

- Plasma undulators

fields in plasmas can be very high, and non-uniform preionisation and plasma resonance can be used for a wide variety of undulator and FEL configurations proposed.

Various aspects:

- "Spontaneous" and "stimulated" radiation.

Depending on conditions, a device can emit "spontaneous" radiation, emit "coherent" radiation on a pre-bunched beam (as in an "optical klystron"), amplify radiation by stimulated emission or oscillate, as the FEL (in different regimes: small or large gain or signal. saturation, amplified spontaneous emission, possibly superradiance).

In the condition of homogeneous broadening ($\Delta\gamma/\gamma < 1/N$, electron beam matched to the em mode (emittances $\epsilon_x = \epsilon_y \sim \lambda/2\pi$, sizes $\sigma_x = \sigma_y \sim L/2\pi$)), with $\bar{K} \sim 1$, at optimum detuning the small signal gain per pass , with Î peak current in Amps, is $g \sim 3 \cdot 10^{-3} \cdot \hat{I} N^2/\gamma$.

If the obtainable Î is supposed to be proportional to $\gamma\epsilon_x\epsilon_y \sim \gamma\lambda^2$, for a given undulator length and period, the gain is proportional to λ^2

At saturation, a fraction $\sim 1/N$ of the beam power can be transformed to em wave (or more if tapered). Amplified spontaneous emission has been observed in the IR and has been studied as a possible VUV source [9].

- to a certain extent, with an undulator, an arbitrary spectrum can be realised with a suitable form of the field [17].

- Polarisation.

Undulators or lasers can produce arbitrary elliptical polarisation [18] on axis (possibly a function of photon energy), possibly modulate it, ...

A circularly polarised laser can be used to measure the polarisation of the electrons in the machine, and has been proposed to polarise the electrons [19].

Description of the radiation distribution.

Reciprocal space. The characteristics of the radiation from a single electron (observation distance >> L) are usually expressed with its spectral-angular distribution ($\omega - \theta$ diagram, with fixed ϕ (azimuth around $\theta = 0$) [11].

This is in fact a form of reciprocal space diagram, if we think that $\omega = k/c$ and $\theta = k_x/k$ (k wavevector, x a transverse coordinate)(only, it is distorted as θ is represented as a coordinate instead of an angle).

Phase space.

At a given ω, radiation as an ensemble of photons in geometrical optics can be described in terms of phase space x, x'= dx/dz, y, y', just like the familiar picture for electrons in machines, with free-space propagation described by a matrix [1,z;0,1], and the phase space density representing the (spectral) "brilliance" $\mathcal{B}$ (also called "brightness" or "radiance").

But also for waves the phase space description can be used [20,21], with the Wigner function

$$\mathcal{B}(x,k_x) = \int E^*(x-u/2)E(x+u/2)exp(ik_xu)du$$

(or the closely related Ambiguity function) representing the phase space density. The surprising consequence is that the evolution equation is identical. The wave nature implies only that $(\lambda/2\pi)^2$ is the minimum ph.sp. volume allowed by "diffraction" (or "uncertainty principle") (this volume is called a "mode"). We can also use ω and t (time) as other two coordinates (and $\Delta\omega\Delta t \geq 1$).

It is convenient to use "reciprocal space" (as in X-ray optics) instead of angles in the definition of the phase space: thus the 6 dimensions are:

x, y, z = ct,

$k_x = kx'$, $k_y = ky'$, $k_z \simeq k = \omega/c$.

With these units, the "mode volume is 1, and the phase space density is expressed by the dimensionless quantity δ, called "degeneracy parameter".

$\mathcal{B}$ and "coherent power" P_c or "coherent flux" Φ_c can be expressed in terms of δ as:

$$\mathcal{B}(phot/sec/0.1\%/mm^2/mrad^2) = 0.7435 \cdot 10^{14} \cdot \delta/\lambda^3(\mu m^3)$$

$$P_c(mW/coh.area \cdot 1\mu m.coh.length) = 0.0148 \cdot \delta/\lambda(\mu m)$$

$$\Phi_c(phot/sec/coh.area \cdot 1\mu m.coh.length) = 0.7435 \cdot 10^{14} \cdot \delta$$

Apart from the convenience of being dimensionless, and giving the same information as $\mathcal{B}$ and P_c, δ, as a number of photons per mode, is an indication of the relative importance of spontaneous and stimulated processes ($\delta >> 1$ and $\delta << 1$ are completely different kinds of em fields).

- radiation from the whole beam: convolution.

A single electron in an undulator of length $L = N\lambda_o$ emits a wave E of wavelength λ, diffraction-limited (and, in time, Fourier-transform limited: $\Delta t \sim hN\lambda$, $\Delta\omega/\omega \sim 1/hN$): the angular aperture at the peak is $\sim (2\lambda/L)^{1/2}$ and the corresponding diffraction size is $\sim (\lambda L/2)^{1/2}/2\pi$ (the transverse phase space volume is $\epsilon_R \sim (\lambda/2\pi)^2$ (wider off-peak).

Electrons are at different phase space positions: each one emits a field around it, so the resulting field is a convolution of the electron distribution $\mathcal{D}(x,x',..)$ with the single-electron field E_1. If the electrons are distributed as a (non-uniform) Poisson process, the Wigner function $\mathcal{B}$ of the radiation is the convolution of $\mathcal{D}$ with $\mathcal{B}_1$ (single-electron Wigner function) [20].

Some consequences of this description are:

- the spatial coherence area in the far-field is $\sim \lambda^2/\sigma$, where σ is the source size (in x or y) (convolution of electron beam size and diffraction).

- when ϵ_R and ϵ (diffraction and beam emittances) are of comparable size, minimum radiation emittance ε is obtained for an "optimum" value of the beam beta function $\beta \sim L/2\pi$. This is important for fel-s, where matching of emittances and beta functions is practically a necessary condition (a lower electron beam emittance is unnecessary and would reduce current).

- for a single electron (or a diffraction-limited beam, $\sigma' < \sigma'_R$), diffraction and depth-of-field blurring of the source are not two distinct phenomena (and should not be added to each other).

Stimulated vs. spontaneous radiation.

Spontaneous and stimulated scattering are connected with each other by a general relationship, independent of the particular system emitting the radiation. This is also practically useful when calculating gain when the spontaneous spectrum is known. This relation is a consequence of the general fact that the probability of emission into a mode of the em field, if it is already occupied by n photons, gets multiplied by n+1. But this relation has also a classical meaning [24], which can be related to the fluctuation-dissipation theorem [25], and can be expressed by saying that the gain is the derivative, with respect to input energy or to ω, of the spontaneous spectral angular intensity [25,26,27].

Related to these are some relations for the energy modulation [28] produced by a wave of intensity I_L of frequency ω_L in a beam emitting a spontaneous spectrum $nG(\omega)$: $\delta\gamma = (4\pi^{3/2}/mc\omega_L)I_L^{1/2}[nG(\omega_L)]^{1/2}$ and the spectral angular distribution S(k) (k = wavevector) of radiation emitted by a modulated beam [29]:

$$S(k) = G(k)(n + \tilde{\rho}(k))$$

, where G is the single-electron spectral-angular distribution, n the number of electrons, $\tilde{\rho}(k)$ the Fourier transform of the electron density $\rho(r)$ (r=x,y,z), the first term being the "incoherent" one and the second one is the "coherent" term, an increase in power due to the electron modulation.

Applications.

The range of photon energies (and corresponding phenomena and applications) is very wide:

- γ-rays from 0.5 MeV to several GeV: nuclear and particle physics.

- X-rays (3-30 KeV) and Hard X-rays (30-500 KeV): crystallography, spectroscopy (edge absorption, Compton, Mössbauer), imaging (tomography, topography)

- Soft X-rays and VUV (10 eV - 3 KeV): Spectroscopy (photoemission, fluorescence), imaging (microscopy, holography, lithography); potential enhancement in the lower energy range with development of FEL.

- UV, visible, IR and Far IR (10 eV - 1 meV): in this range the interest is mainly on FEL: nonlinear and time-resolved spectroscopy, photochemistry, possibly production of strong waves as undulators,..

Requirements

What is a suitable "figure of merit", particularly for an X-ray source? Usually one is interested in having the maximum number $\mathcal{U}$ of "useful" photons.

If we define an acceptance $\mathcal{A}$ in phase space for an experiment plus beamline ($0 \leq \mathcal{A} \leq 1$), $\mathcal{U} = \int \mathcal{A}\mathcal{B}dV$ (where $dV = dxdx'dydy'd\omega dt$, and both $\mathcal{A}$ and $\mathcal{B}$ are propagated to the same position z). If $\mathcal{B}$ contains $\mathcal{A}$ (or can be modified by focussing etc. to contain it), $\mathcal{U}$ is proportional to the maximum value of $\mathcal{B}$. In the opposite case, $\mathcal{U} \sim \mathcal{A}_{max} \int \mathcal{B}dV = \mathcal{A}_{max} \int \Phi d\omega dt$ (in intermediate cases one integrates over the variables for which $\mathcal{A}$ is wider than $\mathcal{B}$.

In other words, for high resolution (in angle, position (small sample) and spectrum) the figure of merit is δ (or $\mathcal{B}$ or P_c), and one would use an undulator (or FEL, if possible), while for low spectral and angular resolution and large samples Φ is relevant, and one would possibly use a wiggler.

In particular, the parameter to be maximised is δ (or $\mathcal{B}$) when the quantity of interest is the intensity (n.phot./area) over any small area, and when it is the number of photons/pixel in a diffraction-limited imaging system.

Practical problems.

Without going into "undulator engineering", but just to give an idea of why reality might be different from ideal models [30], here are some examples:

- imperfections in the magnetic field of undulators broadens peaks and decreases $\mathcal{B}$, particularly on high harmonics [31].

- flux reduction in monochromators.

- slope errors on mirrors (a 1" error can seriously increase the effective source size [32]).

- heating of optical components can produce strong distortions

(in fact, whenever possible, it is convenient to use no optics at all [33]).

- vibrations (control loops necessary for each experiment, which makes control of a synchrotron radiation ring a complicated task)

Some possible developments.

Short periods.

Possible use of short period undulators is of great interest as it could allow the emission of shorter λ for a given machine energy, or the same λ with a lower energy (less expensive) machine. This could be obtained either with permanent magnets and small gaps (microundulators) or with very strong em waves.

For microundulators [34], the analysis of how small a gap can be made in a storage ring is essential, and still requires experimental work. However, while the present experience is in the cm range, theoretical analysis shows that limitations (due to spurious vertical dispersion, residual gas,...) could imply gaps in the 1 mm range, allowing a reduction of a factor 3 in machine energy [34]. Magnetic undulators can be made with periods, say, 0.2 to a few mm by an inexpensive fabrication process on a permanent magnet bloc, while for $\lambda_o \geq 3$ mm sandwitches of hard and soft magnetic materials could be used.

The use of lasers as undulators, on the other hand, requires very high powers: the equivalence with magnetic undulators is given by:

$$\frac{B}{Tesla} \simeq 0.2(\frac{I}{GW/mm^2})^{1/2}$$

(I = intensity (power/area)).

Except for the production of GeV photons (for ex. in LEP), where excimer or Nd lasers can be used to get harder photons, for the use on a low energy machine to get X-rays, a longer wavelength is more convenient, as a CO_2 laser. For ex. on a 100 MeV beam, it could produce 1 Å radiation ($\sim 1.4 \cdot 10^{12} phot/sec/0.1\%$, with 2 GW/mm^2, L=10 cm, 1 A). A transverse laser beam with a cylindrical lens could allow tunability with angle. At longer wavelengths, fel-s themselves could constitute an undulator.

Long undulators on very high energy machines [13,35].

Usually dedicated machines are made with an energy just sufficient to reach the desired wavelengths with a small (cm) gap undulator, so the problem is to obtain the highest magnetic field possible with the shortest possible period. In very high energy machines (10-30 GeV) made for particle physics research (but which can be adapted to run at a very low emittance and used as synchrotron radiation sources, as PEP and Tristan), the electron energy is more than necessary and the periods can be much longer than the gap, and this gives a much greater flexibility: for ex. with a period of 20 cm, to obtain $\bar{K} \sim 1$ requires a field of only ~500 Gauss. This allows not only an easy construction with electromagnets, but also polarisation modulation and even continuous change of period, and partial suppression of the third harmonic. Moreover, as the straight sections in such machines are very long, more than 100 metres, they could accomodate extremely powerful undulators: in particular, amplified spontaneous emission at 40 Å($\sim$ C K-edge) could be an important possibility, and $\delta \sim 1$ could be obtained at 1 or 2 Å (with the ring running at low energy, 4 - 6 GeV.).

Plasma fields.

Very high electric fields can be obtained in plasmas, up to the "Dawson limit". Electrons can travel over distances much shorter than the "Nordsieck length" (for multiple scattering degradation of beam properties), which is inversely proportional to gas density, so the gas density has to be adjusted to compromise between high field and small perturbation.

High electric fields can be obtained in 2 ways:

Plasma oscillations provide a resonance phenomenon that can be used to enhance a longitudinal electric field (with widely tunable wavelength), for ex. like in the proposed beat-wave laser acceleration mechanism[36]. Such a wave, with wavevector perpendicular to the beam, could be a transverse electric undulator.

Strong transient fields can be obtained by a preionisation provided by a pulse of electrons. For ex. a low energy electron pulse in a static magnetic undulator could provide a wiggling ionised channel for higher energy electrons. [37]

Other possibilities.

- modulation of a beam of UV light from an undulator at IR frequencies. A CO_2 laser collinear with electrons (with an undulator) could produce a density modulation of the electron beam, modulating the intensity of the UV light at $3 \cdot 10^{13}$ Hz.

- an FEL made of two different undulators and a dispersive section, as in an optical klystron, with bunch length $< N\lambda$, could be used for double-resonance time-resolved experiments in the IR (?).

- If gravitational waves can be produced by particle beams in magnetic fields [38], then undulators are probably the best sources.

- to suggest other ideas is left as an exercise to the reader.

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