SELF-STIMULATED UNDULATOR RADIATION SOURSES

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Abstract

The phenomena of self-stimulation of incoherent radiation emitted by particles in a system of undulators installed in the linear accelerators or quasi- isochronous storage rings are investigated. Possible applications of these phenomena for light sources are discussed.

INTRODUCTION

A particle passing through an undulator emits an undulator radiation wavelet (URW), the length of which in the direction of its average velocity is $M\lambda_1$, where M is the number of undulator periods, and λ_1 is the wavelength of the first harmonic. In a system of N_u identical undulators, located along straight line, the particle radiates N_u URWs with a separation l; both l and λ_1 are defined by the Doppler effect, by an angle θ between the average particle velocity in the undulator and the direction to the observer, by the distance between the undulators l_0, by the period of the undulator λ_u and by the relativistic factor $\gamma = \varepsilon / mc^2 >> 1$, m_e is the rest electron mass, ε is the electron energy [1], [2]. In the forward direction ($\theta = 0$) they are: $l = l_0 / 2\gamma^2$ and $\lambda_1 \sim \lambda_u / 2\gamma^2$. The energy radiated by a particle in a system of N_u undulators becomes modified and is N_u times larger than one radiated in just a single undulator. The spectrum of radiation emitted in an arbitrary direction also changes, appearing as a line structure. The integrated spectrum does not change much however.

Self-Stimulated Undulator Radiation (SSUR) is a kind of undulator radiation (UR) emitted by a charged particle in a field of the downstream undulator in the presence of self-fields of its own wavelets emitted at earlier times in the same or upstream undulator. These wavelets focused back to the particle's position at the entrance of the downstream undulator with mirrors, lenses and passed through the optical delay lines [3]. Below we considering two schemes based on linear accele-rators and storage rings.

One way to increase the loss rate of a particle in a sys-tem of N_u undulators by the introduction of controlled delays in the motion of the particles between undulators relative to their URWs is shown on the Fig.1.

Delays are chosen so that a particle enters the following undulator in the decelerating phase at the front edge of its URW, which was emitted from preceding one. In this case the particle will experience deceleration in its self-field generated by its instantaneous motion in the field of the undulator as well as in the field of the URW from preceding undulators (stimulated radiation in field of a co-propagating URW). Under such conditions super-position of the wavelets occurs, which yields the electric field growth $\sim N_u$ and the growth of energy density in the emitted radiation becomes $\sim N_u^2$. Below we will name the linear system of undulators and optical elements by self stimulated undulator klystron (SSUK).

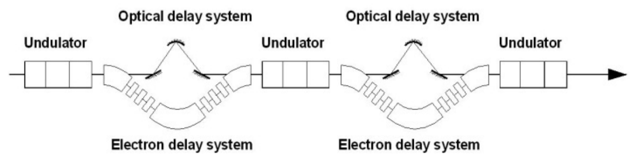

Figure 1: Schematic of the installation.

To be optimally effective, this system must use appropriate focusing elements such as lenses and/or focusing mirrors (see Figs. 1, 2). Mirrors and lenses are used to form a crossover in the middle of the undulators with the Rayleigh length of the order of the length of undulator $Z_R \cong M\lambda_u / 2$.

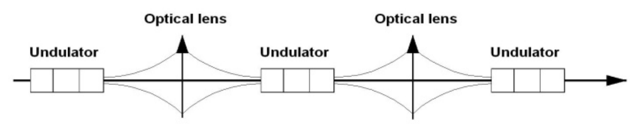

Figure 2: Equivalent optical scheme.

We considered here the case where the optical delays are tuned so that the wavelets emitted by the particle are congruent and all particles stay at the decelerating phase. For this the beam delay system must be isochronous.

Another way to increase the loss rate of a particle is the SSUR source based on a quasi-isochronous storage ring equipped with an undulator (or SSUK) installed in its straight section and the mirrors installed at both sides of the undulators outside of the closed orbits of electrons, circulating in the ring (Fig.3). So the mirrors set an optical resonator.

The scheme of the SSUR source has resemblance to the scheme of ordinary FEL with additional synchronicity condition: the oscillation period of the URW emitted by every electron in the undulator inside the optical cavity coincides with the revolution period of this electron in the storage ring in the limits of energy and transverse emittance of the beam. The URWs emitted by every electron are accumulated effectively in the optical resonator by the superposition one by another if theirs longitudinal shift per turn satisfies condition

$$\Delta\, l - n\lambda_m |\leq \lambda_m / F, \qquad (1)$$

where $\lambda_m = \lambda_1 / m$ is the wavelength of the UR emitted by the electron on the m-th harmonic in the direction of its average velocity, F is the finesse (quality factor) of the optical resonator, $n = \pm 1, \pm 2, ..., |n| \le M$, M is the number of the undulator periods.

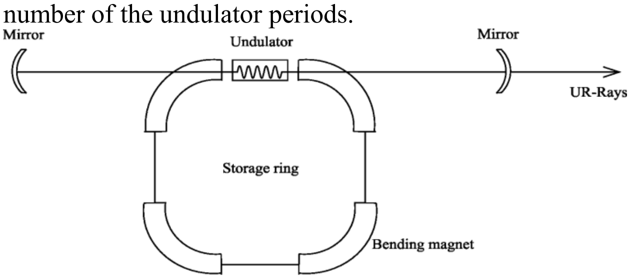

Fig.3. Schematic diagram of SSUR source built around a storage ring.

The condition (1) presents the main synchronicity condition for $n = 1$. There are *2M+1* similar collateral synchronicity conditions corresponding to $1 < |n| < M$ (incomplete overlapping of the URWs).

The general synchronicity condition in the SSUR scheme is as the following

$$\Delta l = | c \cdot \Delta T_{e,URW} | << \lambda_m / F, \qquad (2)$$

where $\Delta T_{e,URW} = T_e - T_{URW}$ is the difference between the revolution periods of the electron in the storage ring and the UWR in the optical resonator. We are considering $T_{URW} = 2L_{mir} / c = const$, $T_e = T_e(\varepsilon, A_b)$, where L_{mir} is the distance between mirrors, A_b is the amplitude of the electron betatron oscillations. The value $\Delta T_{e,URW}$ can be presented in the form

$$\Delta T_{e,URW} = \Delta T_\eta + \Delta T_{A_b}, \qquad (3)$$

where in the smooth approximation $\Delta T_\eta = \eta_c \cdot T \cdot \Delta\varepsilon / \varepsilon$, $c \cdot \Delta T_A = \pi^2 A^2_{b,x,z} \nu_x^2 / C$, $\beta_{x,z} \simeq \overline{\beta}_{x,z} = C / 2\pi\nu_{x,z}$, $\eta_c = 1/\gamma^2 - \alpha_c$ is the phase slip factor of the ring, C – is the circumference of the electron orbit, $A_{b,x,z}$, $\beta_{x,z}$, $\nu_{x,z}$ are the horizontal/vertical amplitudes, β - functions and tunes of electron betatron oscillations accordingly, α_c is the momentum compaction factor of the ring. For relativistic electron beams $\eta_c \simeq -\alpha_c$. Synchronicity condition determines the limiting energy spread, amplitudes of betatron oscillations and emittance of the electron beam:

$$\Delta\varepsilon_r / \varepsilon < \lambda_m / CF\eta_c, \; A_{b,x,z} < \sqrt{\lambda_m \, \lambda_{x,z} / F\nu_{x,z}} / \pi,$$

$$\epsilon_{x,z} < 2\lambda_m / \pi F \nu_{x,z}, \qquad (4)$$

where $\lambda_{x,z} = C / \nu_{x,z}$ is the wavelength of the betatron oscillations. Note that the last inequality in (4) $\nu_{x,z} F / 4 > 1$ times stronger than one for the diffraction limited electron beam

Note, that if the energy spread of the beam $\Delta\varepsilon_b$ is much bigger than the limiting one $\Delta\varepsilon_r$, then *~2M+1* collateral synchronicity conditions $\Delta l_\eta = c\Delta T_\eta = \pm n\lambda_m$ can occur simultaneously. In this case the acquired relative energy spread of the beam:

$$\Delta\varepsilon_b / \varepsilon < 2M\lambda_m / C\eta_c. \qquad (5)$$

The requirements to the beam emittance for the collateral synchronicity conditions stay (4). They are less severe than ones for the limiting energy spread $\Delta\varepsilon_r$.

Requirements to the electron beam energy spread and emittance are increased with the hardness of the UR $\hbar\omega_m = 2\pi\hbar c / \lambda_m$. It is difficult to obtain the energy spread of the electron beam $\Delta\varepsilon_r / \varepsilon$ necessary for synchronicity conditions in the X-ray region ($\lambda_m \sim 1A^0$), but it is possible to obtain the energy spread $\Delta\varepsilon_b / \varepsilon$ and to work with the main and collateral synchronicity conditions ($0 <| n |< M$). Remarkable part of electrons in the beam will work effectively in this case. The transient behavior of the power of the emitted undulator radiation can be used for its amplification [4].

By using a linear system of N_u pickup undulators, SSUK, (see Figures 1, 2) located along the straight section of the storage ring one can amplify this process N_u^2 times.Note that for the SSUK the requirements to the bunch parameters are much easier then (4). They are determined by (4) if we replace C on l_0, η_c on $\eta_{c,l}$, $\lambda_{x,z}$ on l_0, and suppose $\nu_{x,z} = F = 1$, where $\eta_{c,l}$ is the local slip factor do not burden by the auto phasing problem. Note that there are no problems to produce the isochronous linear system of undulators with the zero local slip factor in optical region [5].

SPONTANEOUS INCOHERENT SSUR SOURCES

Obviously, all properties of the spontaneous incoherent radiation emitted by the electrons in a SSUR source under main synchronicity condition $n = 0$ are not changed, except intensity, which becomes higher by $F / 2\pi$ times. At collateral synchronicity conditions (|*n*| > 0) the URWs emitted by an electron at each pass through the undulator are shifted by the distances $\pm\lambda_m, \pm 2\lambda_m, ... \pm n\lambda_m$, $\cdots \pm M\lambda_m / 2$ with the gaps $\Delta l \le \lambda_m / F$ for the next URW relative to previous one and the properties of radiation are different: the intensity is dropped, but the monochromaticity is increased with the number *n*.

The scheme of the SSUR source requires an electron beam with ultralow transverse emittance, energy spread and an optical resonator with high finesse (quality factor). This is possible in cm to optical and UV regions. X-ray mirrors applicable for the Light Sources (LS) now are the mirrors based on the Bragg scattering. These mirrors effectively reflect radiation in a very narrow spectral range $\Delta\omega_{refl}$ ($\hbar\Delta\omega_{refl} \sim 1 \; meV$). The intensity reflection coefficient in this frequency range can be high $r_{Br} \simeq 1 - 2\pi / F_{refl} \simeq 0.99$ and near to zero ($r_{Br} \simeq 0$) in the rest spectral region. The total energy of the URWs during round trip reflection will be decreased $r_{Br} r^{-1}_{Br,tot} = \Delta t_{refl} / \Delta t_{URW} = M_{refl} / M >> 1$ times, where

$\Delta t_{refl} = T_1 M_{refl}$ is the duration of the reflected URW, $T_1 = 2\pi/\omega_1$, $M_{refl} = \hbar\omega_1/\Delta(\hbar\omega)_{refl} \simeq 10^6 - 10^7$ is the number of cycles in the reflected URW. The degree of monochromaticity $\Delta\omega/\omega$ and coherence length of the reflected URW $l_{refl} = c\Delta t_{refl}$ will be increased $r^{-1}_{Br,tot}$ times.

The fronts of URWs reflected by Bragg mirrors will coincide with the initial ones. Electrons will emit their URWs at different moments of time in the limits of the electron bunch current duration Δt_b. The lengths of the reflected URWs $l_{refl} = \lambda_1 M_{refl}$ can be much larger than the bunch length $l_b = c\Delta t_b$. In this case the UR bunch after reflections in the resonator will be presented by one long ($l_{refl} >> l_b$) nearly pure sine wave except short ($\sim l_b$) head and tail parts of the beam.

SSUR SOURCES AND FREE-ELECTRON LASERS

One important peculiarity of the source suggested here is that there is no requirement for the coherence in radiation among different electrons in the bunch like it is required for the prebunched FELs including ones based on isochronous storage rings. Electrons in this source are not grouped in micro-bunches with the longitudinal dimension $\sigma_{\|} << \lambda_m$, separated by the distances which are integers of λ_m. Stimulated process of radiation for each electron is going in the undulator with their own URW fields only. Every electron enters the undulator together with its URWs emitted at the earlier times [3].

When we are talking about a quasi-isochronous storage ring we have in mind that round trip slip factor of the ring is set near to zero. At the same time the local slippage factor can be high in the region occupied by the undulators. It means that bunching of the beam and the emission of coherent UR can be produced by external electromagnetic wave in the undulator or in the SSUK (undulator/optical klystron mechanism). If the large number of electrons satisfying to the synchronicity conditions are located on the length of the URWs $M\lambda_1$ (coherence length, sample) then stimulation of SASE regime by high value seeding URWs from sub-regions satisfied to the synchronicity conditions will appear. Self-bunching will appear as well. In this case outside the undulator or SSUK the bunching can be lost but it will appear again and will be amplified in addition to the previous one by stored co-propagated URWs for the next turns through the same undulator or SSUK. By such way stimulation of the oscillator X-ray free-Electron laser regime under the main and collateral synchronicity conditions can be produced.

CONCLUSION

The phenomenon of self-stimulated incoherent emission of the UR in the SSUKs and quasi-isochronous storage rings is investigated. The requirements to the beam parameters and the degree of synchronicity are evaluated for the SSUR source based on a quasi-isochronous storage ring. We hope that SSUR source based on either the ordinary and compact storage rings using the static or laser undulators, electron or ion beams, ordinary or Bragg resonators will be able to generate both short and continuous, quasi-monochromatic light beams in the optical to X-ray regions.

A transient behavior of the amplitude and the power of the URWs are investigated. It was shown that these values are the quasi-periodic functions of the revolution number in the time interval determined by damping time of the URW in optical resonator. At this interval the power of emitted radiation can be much higher than its steady state value. That is why the emitted power can be increased if the energy of optical beam stored in the resonator will be extracted periodically (or, if the phase of the stored radiation in the URWs will be changed to π) for one revolution of the beam in the ring (overload conditions).

SSUKs could be used effectively both in ordinary and prebunched FELs.

More full statement of the considered and another similar questions see [4].

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