IL NUOVO CIMENTO Vol. 34 C, N. 4 Luglio-Agosto 2011
DOI 10.1393/ncc/i2011-10967-9

Colloquia: Channeling 2010

Self-stimulated undulator radiation and its possible applications

E. G. Bessonov(1), M. V. Gorbunkov(1), A. A. Mikhailichenko(2), A. L. Osipov(1) and A. V. Vinogradov(1)

(1) *RAS P.N. Lebedev Physical Institute - 119991 Moscow, Russia*
(2) *Cornell University, LEPP - Ithaca, NY 14853, USA*

(ricevuto il 22 Dicembre 2010; pubblicato online il 19 Settembre 2011)

Summary. — The phenomena of self-stimulation of incoherent undulator radiation (UR) 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 the beam physics and light sources are discussed.

PACS 41.60.Cr – Free-electron lasers.
PACS 41.75.Lx – Other advanced accelerator concepts.

1. – Introduction

Self-Stimulated Undulator Radiation (SSUR) is a radiation emitted by a charged particle in the field of a downstream undulator in the presence of self-fields of its own UR wavelets (URW) emitted at earlier times in the same or upstream undulator [1]. Below we considering two schemes of continuous, quasi-monochromatic SSUR production in the optical to X-ray regions. Requirements to the parameters of particle beams and to the magnetic lattices are evaluated. Cooling of the particle beams based on emission of the SSUR in storage rings is considered.

2. – SSUR source based on the linear system of undulators

A particle passing through an undulator emits an URW, the length of which is $M\lambda_1$, where M is the number of undulator periods, and λ_1 is the wavelength of the first harmonic of the UR. In a system of N_u identical undulators, located along a 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 undulators l_0, by the period of the undulator λ_u and by the relativistic factor $\gamma = \varepsilon/m_e c^2 \gg 1$, where m_e is the rest electron mass, ε is the electron energy. In the forward direction ($\theta = 0$) these numbers are: $l = l_0/2\gamma^2$, $\lambda_1 = \lambda_u(1 + K^2)/2\gamma^2$, where $K = \sqrt{\overline{|\vec{p}_\perp|^2}} = e\sqrt{\overline{|\vec{B}_\perp|^2}}\lambda_u/2\pi m_e c^2$ is the deflection parameter of the undulator, $\vec{p}_\perp = \gamma\vec{\beta}_\perp$, $\vec{\beta}_\perp = \vec{v}_\perp/c$ is the transverse relative electron velocity exited by the undulator field, $\overrightarrow{B}_{\perp}$ is the transverse component of the magnetic field strength vector [2]. The energy radiated by a particle is N_u times larger than the one radiated in just a single undulator. The spectrum of radiation emitted in any direction has a line structure. The integrated spectrum does not change much [3, 4]. The system of two undulators is named undulator klystron (UK) [5]. The UK with dispersion element between undulators is known as optical klystron (OK) [6].

In the publication [1] a way to increase the loss rate of a particle in a system of N_u undulators by the introduction of mirrors, lenses and delay lines was suggested. Controlled delays in the motion of the URWs between mirrors and the particles between undulators are used in this scheme. 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 the preceding one. In this case the particle experiences deceleration in 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). Under such conditions superposition of the wavelets occurs, which yields the electric field strength growth $\sim N_u$ and the growth of energy density becomes $\sim N_u^2$. Below we will call the linear system of undulators and optical elements "self-stimulated undulator klystron" (SSUK). To be optimally effective, this system must use appropriate focusing elements such as quadrupole and optical lenses, bending magnets, focusing mirrors. Mirrors and lenses are used to form a crossover in the middle of the undulators with the Rayleigh length of the order of the undulator length: $Z_R \cong M\lambda_u/2$. We consider here the case where the optical delays are tuned so that the wavelets emitted by the particle are congruent and every particle stays at the decelerating phase of its URWs. For this the electron beam delay system of the SSUK must be isochronous.

3. – SSUR source based on storage rings

The SSUR source is based on a quasi-isochronous storage ring equipped with an undulator installed in its straight section and the mirrors installed at both sides of the undulator outside of the closed orbits of electrons, circulating in the ring. 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 revolution period of electrons in the storage ring does not depend on their energy and amplitudes of betatron oscillations in the limits of the energy spread and transverse emittance of the beam and equal to the oscillation period of the URWs in the optical resonator.

The URWs emitted by every electron are accumulated effectively in the optical resonator by the superposition of one on the other if their longitudinal shift per turn is

$$|\Delta l| \leq \lambda_m/F, \tag{1}$$

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. The condition (1) presents the main synchronicity condition. In the general case there are $2M + 1$ similar collateral synchronicity conditions corresponding to incomplete overlapping of the URWs

$$|c \cdot \Delta T_{e,\mathrm{URW}} - n\lambda_m| \ll \lambda_m/F, \tag{2}$$

where $\Delta T_{e,\mathrm{URW}} = T_e - T_{\mathrm{URW}}$ is the difference between the revolution periods of the electron in the storage ring and the UWR in the optical resonator, $n=0, \pm 1, \ldots, |n| \leq M$. We are considering $T_{\mathrm{URW}} = 2L_{\mathrm{mir}}/c = \mathrm{const}$, $T_e = T_e(\varepsilon, A_b)$, where L_{mir} is the distance between mirrors, A_b is the amplitude of the electron betatron oscillations. The value $\Delta T_{e,\mathrm{URW}}$ can be presented in the form $\Delta T_{e,\mathrm{URW}} = \Delta T_\eta + \Delta T_{A_b}$, where in the smooth approximation $\beta_{x,z} \simeq \overline{\beta}_{x,z} = C/2\pi\nu_{x,z}$

$$(3) \qquad \Delta T_\eta = \eta_c \cdot T \cdot \Delta\varepsilon/\varepsilon, \qquad c \cdot \Delta T_A = \pi^2 A^2_{b,x,z}\nu_x^2/C,$$

$\eta_c = 1/\gamma^2 - \alpha_c$ is the phase slip factor of the ring [7, 8] C is the circumference of the electron orbit, $A_{b,x,z}$, $\beta_{x,z}$, $\nu_{x,z}$ are the horizontal/vertical amplitudes, β the functions and tunes of electron betatron oscillations accordingly, α_c is the momentum compaction factor of the ring [8]. 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:

$$(4) \qquad \Delta\varepsilon_r/\varepsilon < \lambda_m/CF\eta_c, \qquad A_{b,x,z} < \sqrt{\lambda_m\lambda_{x,z}/F\nu_{x,z}/\pi}, \qquad \in_{x,z} < 2\lambda_m/\pi F\nu_{x,z},$$

where $\lambda_{x,z} = C/\nu_{x,z}$ is the wavelength of the betatron oscillations. Note that the last inequality in (4) is $\nu_{x,z}F/4 > 1$ times stronger than that for the diffraction limited electron beam. The used smooth approximation permits to appreciate the expressions for requirements to the storage ring.

In order that URWs emitted in the direction of the undulator axis overlap effectively, they must have small spread of the carrier frequency. It follows that the requirements to the energy and angular spreads of the electron beam and its emittance should be

$$(5) \quad \Delta\varepsilon/\varepsilon \ll 1/m \cdot M, \qquad \Delta\theta \ll 1/\gamma\sqrt{m \cdot M}, \qquad \in_{x,z} = \overline{\beta}_{x,z} \cdot (\Delta\theta)^2 < \lambda_m\lambda_{x,z}/\pi L_u.$$

Usually the values $\lambda_m/C \cdot F \cdot \eta_c \ll 1/mM$, $F \gg 2L_u/C$. That is why conditions (5) are less severe than (4).

Note that if the energy spread of the beam $\Delta\varepsilon_b$ is much larger than the limiting one $\Delta\varepsilon_r$, then, according to (2) $\sim 2M+1$ collateral synchronicity conditions $\Delta l_n = c\Delta T_\eta = \pm n\lambda_m$ can occur simultaneously at the energies determined by the different numbers n for the energy intervals and amplitudes determined by (4). For $|n| = M$ the acquired relative energy spread of the beam is $2MF$ times bigger:

$$(6) \qquad \Delta\varepsilon_t/\varepsilon < 2M\lambda_m/C\eta_c.$$

The equality $c \cdot \Delta T_{e,\mathrm{URW}} = n\lambda_m$ determines the energy of the corresponding collateral synchronicity condition $\gamma_{\mathrm{col},n}$. The spectrum of the UR emitted by the electron beam under the condition $\Delta\varepsilon_b > \Delta\varepsilon_t$ will have pips at the wavelengths $\lambda_{m,n} = \lambda_m(\gamma_{\mathrm{col},n})$ corresponding to the number n of the synchronicity condition.

Example. Let $\lambda_m = \lambda_1 = 1\,\mathrm{mkm}$, $C = 100\,\mathrm{m}$, $\eta_c = 10^{-5}$, $\nu_x = 2.5$, $F = 31.4$, $M = 30$. In this example, according to (4), the electron beam for the main synchronicity condition must have the emittance $\in_{x,z} < 8.1\,\mathrm{nm}$, energy spread $\Delta\varepsilon_r/\varepsilon \ll 3.2 \cdot 10^{-5}$, $\Delta\varepsilon_b/\varepsilon \gg 3.01 \cdot 10^{-2}$ and amplitudes $A_{z,x} \ll 0.22\,\mathrm{mm}$. These requirements to the electron beam emittance in the optical region are acceptable for the 2nd Generation Light Sources (GLSs). At the same time the requirements to the electron beam energy spread $\Delta\varepsilon_r/\varepsilon$ are severe for the modern 3rd, future 3.5th Generation Light Sources (GLSs) [9] and for the LSs using multi-turn recirculation of the ultralow emittance electron beams in the energy recovery storage rings [10-13].

If we accept that the normalized transverse beam emittance is $\in_n = 0.1\,\mathrm{mm}\cdot\mathrm{mrad}$ and the relative energy spread is $\Delta\varepsilon_b/\varepsilon \ll 10^{-4}$, then at the energy $\varepsilon = 5\,\mathrm{GeV}$ ($\gamma = 10^4$) the geometrical emittance will be equal to $\in = 10^{-11}\,\mathrm{m}$. These beam parameters are typical for the advanced 4th GLSs under development and are one order of magnitude lesser than for 3rd GLSs [14]. 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 ($\lambda_m \sim 1\,\text{Å}$), but it is possible to obtain the energy spread $\Delta\varepsilon_t/\varepsilon$ 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.

One of the main problems in the considered scheme of the SSUR source is the condition of synchronicity (2) valid for all electrons of the beam simultaneously. It can be realized in a quasi-isochronous storage ring ($|\eta_c| \ll 10^{-5}$). "Such rings do not yet exist at this time but are intensely studied and problems are being solved in view of great benefits for research in high energy physics, synchrotron radiation sources, and free electron lasers to produce short electron or light pulses" [8] (p. 303). To the present day all projects and experiments were done with existing storage rings converted to isochronous ones by some changes in theirs lattices. The problem of optimal isochronous storage ring for any given purpose is not solved. "Let us assume that one has a storage ring and wants to adjust the lattice settings to obtain certain properties such as low emittance or a small momentum compaction, etc. Determining how to adjust the lattice to achieve certain properties is not a straightforward process. The process is actually blind and involves a lot of trial and error. In many ways it is an art which is aided by the instincts and experience of the practitioner" [15]. Here we would like to underline that the lattice can be constructed in a such way that the slip factor will reach zero value, cross it or will have minimum at given energy of the electron. The regions of the energy and amplitudes (4) appear which satisfy the synchronicity condition (2). The problem is in the development of a lattice for the quasi-isochronous storage ring, which has given small slip factor at a given energy and weak dependence on their momentum and amplitudes of betatron oscillations. The problems associated with isochronous storage rings can be facilitated as well if the phase focusing is rejected and the ring is forced to work with low-friction particles (ion and muon beams, low energy electron beam) and the eddy fields or phase displacement mechanisms.

The energy of the URW and the number of the photons emitted into TEM_{00} mode for a single pass are

$$\Delta\varepsilon_{\mathrm{URW},1} = 32\pi e^2 K_\perp^2/\lambda_1(1+K^2), \qquad N_\gamma = 16\alpha K^2/(1+K^2), \tag{7}$$

where $\alpha = e^2/\hbar c = 1/137$. Non-synchronous condition of the resonator excitation $\Delta l \neq 0$ can be investigated by analogy with excitation of resonators by the periodic electron bunches in the parametric FELs. In this case the behavior of the energy variation of the URW in the optical resonator is similar to the time dependence of the energy of an oscillator excited by an external force [16, 17].

4. – Cooling of electron and ion beams based on the SSUR

There are two ways to the particle beam cooling. They are based either on friction (frictional force is directed against the particle velocity) or on the finite quantity inter-particle spacing (follow the particle of the beam and force the particle to shift to the center of the beam) [18, 19]. In any case personal force must be applied to each particle. External fields and self-fields produced by particle beam do not lead to cooling as they act upon all particles independently of the value and direction of their velocities.

4˙1. *Frictional cooling of particle beams.* – According to the generalized Robinson damping criterion for the frictional cooling, the rate of the 6D beam density change is determined by the damping decrement

$$\alpha_{6\mathrm{D}} = \left(1 + \frac{1}{\beta^2}\right) \frac{\overline{P}_{Fr}(\varepsilon)}{\varepsilon} + \frac{\partial \overline{P}_{Fr}(\varepsilon)}{\partial \varepsilon}\,, \tag{8}$$

where $\overline{P}_{Fr}(\varepsilon)$ is the power of the electromagnetic radiation emitted by the particle [19]. Different parts of the beam in the phase space volume occupied by the beam can have different rates of cooling if $\overline{P}_{Fr}(\varepsilon)$ is a non-linear function of ε. In case of SSUR, the value $\partial \overline{P}_{Fr}(\varepsilon)/\partial \varepsilon$ at $\eta_c \neq 0$ strongly depends on the deviation of the particle's energy on the energy corresponding to the condition of main or collateral synchronicity.

If the optical resonator is switched off, then the frictional power $\overline{P}_{Fr}(\varepsilon) \sim \varepsilon^2$. That is why in the relativistic case the first and second terms in (8) are equal. If the resonator is turned on, the power $P_{Fr}(\varepsilon, t)$ at the energy corresponding to the synchronicity condition is increased $\sim F/2\pi$ times and, according to (4), (5), the partial derivative $\partial \overline{P}_{Fr}(\varepsilon)/\partial \varepsilon$ at the bias of the dependence $\overline{P}_{Fr}(\varepsilon)$ is increased $\sim (F/2\pi)(\varepsilon/2\Delta\varepsilon) = CF^2\eta_c/4\pi\lambda_m$ times. That is why the second term in (8) will be $CF^2\eta_c/4\pi\lambda_m$ times higher than the first one and the damping time will be correspondingly smaller. If we introduce in the optical resonator an amplifier and regulate in time the delay line, then the possibility will appear to move the energy corresponding to the synchronicity condition down and to gather the dense particle beams at a lower energy (the analogy of the frequency chirp for the laser cooling of ion beams). The efficiency of this scheme can be increased if we will turn on the amplifier per duration of the particle bunch for some time, then turn it off, removing by this way the stored laser energy from the resonator per one revolution and repeat this process many times. Different schemes of cooling can be considered (RF accelerating fields are switched on/off, eddy fields or phase displacement mechanisms are used, or their combinations).

4˙2. *Optical cooling of particle beams.* – Let us remind here that for any method of Optical Stochastic Cooling (OSC) it is important to emit as many photons as possible in the spectral bandwidth $\Delta\lambda/\lambda \leq 1/2M$ and in the angles $\Delta\theta \leq 1/\gamma\sqrt{M}$ [20-23]. The number of photons within this angular and energy spread does not depend on the length of the undulator. So, for example, the use of three pickup undulators in SSUK is 3 times more effective in the emitted field strengths and 9 times more effective in the emitted energy (in the number of emitted photons) than just in a single pickup undulator. This also means that usage of such system with three pickup undulators and a single kicker for OSC is 3 times more effective for damping, than a single pickup and a single kicker. So the effectiveness of the pickup and kicker SSUK system consisting of N_u undulators each is proportional to N_u^2.

The ratio of the number of the photons emitted in the pickup SSUK to the number of noise photons is a very important parameter for all methods of optical cooling. Another important item is the destructive interference with URWs radiated by other particles. This process is similar to OSC, leading to the reduction of cooling process proportional to

$1/\sqrt{N_{bw}}$, where $N_{bw} \cong NM\lambda_1/l_b$, stands for the number of particles in the bandwidth, l_b is the bunch length and N is its population.

5. – Light Sources based on self-stimulated incoherent UR

The SSUR source requires an electron beam with ultralow transverse emittance, energy spread, SSUK and an optical resonator with high-finesse mirrors (quality factor). High-finesse resonators and mirrors are possible in cm to optical and UV regions. Very high finesse (above 10^6) can be achieved either by using the dielectric super-mirrors or in certain microcavities based on whispering gallery modes [24]. The problem of X-ray mirrors is not solved and is still very important. The only versions for such mirrors applicable for Light Sources (LS) now are the mirrors based on Bragg scattering [25-30]. These mirrors effectively reflect radiation in a narrow spectral range. For normal incidence the reflection of X-rays from the diamond under the Bragg condition could approach 100%—substantially higher than for any other crystal. Commercially produced synthetic diamond crystals demonstrate an unprecedented reflecting power at normal incidence and millielectronvolt-narrow reflection bandwidths for hard X-rays [31]. Electron beams with normalized emittance 1 mm mrad exist now. One order smaller emittances are under discussion.

The power of the SSUR source using mirrors which reflect radiation in a broadband spectral range in the case $\Delta\varepsilon_b/\varepsilon = 0$, $\eta_c = 0$, $\in_{x,z}= 0$ and under the general synchronicity condition ($n = 0$, $\Delta l = 0$) will be $F/2\pi$ times higher than the spontaneous incoherent one acquired by the resonator TEM_{00} mode outside of the synchronicity condition. Other properties of the spontaneous incoherent radiation emitted under the main synchronicity condition are not changed. If $n = 0$ and $0 < \Delta l < \lambda_m/4$, then the intensity will be increased by a lower degree but the monochromaticity will be increased. Under the collateral synchronicity condition corresponding to the contact between the neighboring URWs ($|n| = M$), the power of the SSUR will be equal to the incoherent one but the monochromaticity will be increased $F/2\pi$ times (similar to the case of parametric FELs [16]) as the length of the effective URW l^{ef}_{URW} will be $F/2\pi$ times bigger. If in this case the length of the electron bunch $l_b \ll l^{ef}_{\mathrm{URW}}$, then both every emitted URW and the total bunch of the UR (the sum of the emitted URWs) will be described (except a part of the length l_b for total bunch) by approximately pure sine wave with slowly decreased amplitude. The power in the UR is equal to the power of the spontaneous incoherent radiation.

Note that the spontaneous incoherent UR outside of the synchronicity condition consists of a large number of short independent URWs. In this case if $l_b \gg l_{\mathrm{URW}}$, then there is no phase correlation between the URWs and the form of the total electric field strength in the UR bunch is far from the sinelike one.

If the smallness conditions (4) for the energy spread and the emittance are violated, then in the 6D phase space region occupied by the electron beam $\sim 2M$ sub-regions satisfied by the collateral synchronicity conditions (2) appear. However the effect on the total power and the degree of monochromaticity for such beam will not be high because the phase space volume occupied by sub-regions is less than the total 6D volume even for the beam energy spread equal to (6). The transient behavior of the power of the emitted undulator radiation can be used for the amplification [17]. By using a SSUK consisting of N_u undulators located along the straight section of the storage ring one can amplify the power N_u^2 times.

Note that for the SSUK the requirements to the bunch parameters are much easier than (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 not loaded by the autophasing problem [20]. There are no problems to produce a high-degree quasi-isochronous linear system of undulators with a small local slip factor in the optical region [32].

The SSUR source using Bragg reflecting crystal mirrors reflect radiation in a narrow spectral range $\Delta\omega_{\rm refl}$ ($\hbar\Delta\omega_{\rm refl} \sim 1\,{\rm meV}$). The intensity reflection coefficient in this frequency range can be high, $r_{\rm Br} \simeq 1 - 2\pi/F_{\rm refl} \simeq 0.99$ and near to zero in the rest spectral region. The total energy of the URWs during reflection will be decreased $r^{-1}_{\rm Br,tot} = \Delta t_{\rm refl}/\Delta t_{\rm URW} = M_{\rm refl}/M \gg 1$ times, where $\Delta t_{\rm refl} = T_1 M_{\rm refl}$ is the duration of the reflected URW, $T_1 = 2\pi/\omega_1$, $M_{\rm refl} = \hbar\omega_1/\Delta(\hbar\omega)_{\rm refl} \simeq 10^6$–$10^7$ is the number of cycles in the reflected URW. The degree of monochromaticity $\Delta\omega/\omega$ and coherence length of the reflected URW $l_{\rm refl} = c\Delta t_{\rm refl}$ will be increased $r^{-1}_{\rm Br,tot}$ 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 $l_{\rm refl} = \lambda_1 M_{\rm refl}$ 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 ($l_{\rm refl} \gg l_b$) nearly pure sine wave except short $\sim l_b$ head and tail parts of the beam.

X-ray version of spontaneous incoherent high-degree monochromatic SSUR source based on the Bragg reflecting crystal mirrors could be effective if quasi-isochronous storage rings, ultralow emittance electron or cooled ion beams high-finesse mirrors and colleteral synchronicity conditions are used. Backward Compton scattering sources based on compact lattices and laser undulators can be discussed as well. Use of SSUK with much smaller local slip factor will allow to increase the generated power essentially.

One important peculiarity of the SSUR 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 parametric/prebunched FELs [33-35] including those based on isochronous storage rings [36, 37]. Electrons in this source are not grouped in microbunches with the longitudinal dimension $\sigma_{||} \ll \lambda_m$, separated by the distances which are integers of λ_m. Stimulated process of radiation for each electron occurs in the undulator with its own URW fields only. Every electron enters the undulator together with its URWs emitted at earlier times [1].

6. – SSUR sources and Free-Electron Lasers

We have considered a case, in which the URWs are emitted in the SSUK by each particle independently. The same consideration is still valid for a single microbunch with the number of particles N_1 and the length $l_{\rm mkb} \ll \lambda_1$ (such microbunch is equivalent to a particle with charge eN_1) or for the trains $N_{\rm mkb}$ of such microbunches in a parametric (prebunched) Free Electron Lasers (FEL) [38]. In this case the power emitted is $P \sim N_1^2 N_u^2$. The FEL system which consists of a modulator undulator with the laser beam and the SSUK installed in a storage ring (as well as in ordinary or energy recovering linacs and recirculators) can be used by analogy with the scheme considered in [39].

When we are talking about a quasi-isochronous storage ring we have in mind that the 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 SSUK. In this case outside the undulator the beam bunching can be lost but it will appear again at the next turns of the beam [36,37]. The bunching will be amplified by self-fields of the bunched beam or/and stored co-propagated URWs in the optical resonator if the synchronicity condition for SSUR will be fulfilled. By such way stimulation of the oscillator X-ray free-electron laser regime under the main and collateral synchronicity conditions can be produced. The RF accelerating system in this case must be switched off and other nonresonance schemes of electron acceleration can be switched on (the eddy fields or phase displacement mechanisms and so on).

If a large number of electrons satisfying to the synchronicity conditions (2) are located on the length of the URWs $M\lambda_1$ (coherence length, sample), then stimulation of SASE regime in FEL based on SSUK and quasi-isochronous storage rings by high value seeding self-stimulated UR wavelets (SSURWs) emitted by electrons in sub-regions satisfied by the synchronicity conditions will appear. Self-bunching will appear as well.

7. – Conclusion

The phenomenon of SSUR in the SSUKs and quasi-isochronous storage rings is investigated. The requirements to the beam parameters and the degree of synchronicity are evaluated. The schematic SSUK could be used effectively in different methods of optical cooling of particle beams in ordinary (non-isochronous) damping rings [20-23]. So these systems can serve as an effective pick-up undulator, for example.

* * *

This work was supported by RFBR under Grants No. 09-02-00638a, 09-02-01190a.

REFERENCES

[1] Bessonov E. G., Gorbunkov M. V., Mikhailichenko A. A. and Osipov A. L., *J. Instrum.*, **5** (2010) 1, arXive: `http://arxiv.org/abs/1003.3747`.

[2] Bessonov E. G., *Light sources based on relativistic electron and ion beams*, presented at *International Conference on Charged and Neutral Particles Channeling Phenomena II, Channeling 2006*, edited by Dabagov Sultan B., published in *SPIE*, Vol. **6634**, 66340X-1 66340X-14.

[3] Bessonov E. G., *Nucl. Instrum. Methods A*, **341** (1994) ABS 87.

[4] Bessonov E. G., *Undulators, undulator radiation, free-electron lasers*, in *Proc. Lebedev Phys. Inst.*, edited by Basov N. G. and Cherenkov P. A. (Lebedev Phys. Inst., Moscow) 1993, pp. 3–119.

[5] Phillips R. M., *IRE Trans. Electron Devices E*, **D-7** (1960) 231.

[6] Vinokurov N. A. and Skrinsky A. N., preprint INP N77-59, Novosibirsk (1977).

[7] Corbett W. J., Donald M. H. R. and Garren A. A., *An isochronous lattice for pep*, in *Proceedings of PAC 1991* (1991), p. 2868.

[8] Wiedemann H., *Particle Accelerator Physics*, 3rd edition (Springer-Verlag, Berlin, Heidelberg) 2007.

[9] Gruner S. M., Bilderback D., Bazarov I., Finkelstein K., Krafft G., Merminga L., Padamsee H., Shen Q., Sinclair C. and Tigner M., *Rev. Sci. Instrum.*, **17** (2002).

[10] Nakamura T., *Phys. Rev. ST Accel. Beams*, **11** (2008) 032803.

[11] Shoji Y., Hisaoka Y., Matsubara T., Mitsui T., Asaka T. and Suzuki S., *Circulation of a short, intense electron bunch in the newsubaru storage ring*, in *Proceedings of EPAC 2006*, pp. 163–165.

[12] Suzuki S., Asaka T., Matsubara T., Mitsui T., Hisaoka Y. and Shoji Y., *Bunch compression using the transport line and short bunch revolving in newsubaru*, in *Proceedings of Apac 2007*, pp. 619–621.

[13] Shoji Y., Hisaoka Y., Matsubara T. and Mitsui T., *Longitudinal coherent oscillation induced in quasiisochronous ring*, in *Proceedings of Epac 2006*, pp. 1972–1974.

[14] Elleaume P. and Ropert A., *Nucl. Instrum. Methods Phys. Res. A*, **500** (2003) 1824.

[15] Robin D. S. and Wan W., *Exploring the limits of the als triple bend lattice*, *Pac07*, pp. 1188-1190.

[16] Alexeev V. I., Bessonov E. G. and Serov A. V., *Nucl. Instrum. Methods A*, **282** (1989) 439.

[17] Bessonov E. G., Gorbunkov M. V., Mikhailichenko A. A., Osipov A. L. and Vinogradov A. V., *Self-stimulated undulator radiation and its possible applications*, arXiv:1009.3724, `http://arxiv.org/abs/1009.3724` (2010).

[18] Bessonov E. G., *Methods of charged particle beam cooling*, in *Proceedings of Charged and Neutral Particles Channeling Phenomena - Channeling 2008, the 51st Workshop of The INFN Eloisatron Project*, edited by Dabagov S. B. and Palumbo L. (World Scientific) 2010, pp. 606–618.

[19] Bessonov E. G., *The evolution of the phase space density of particle beams in external fields*, in *Proceedings of The Workshop on Beam Cooling and Related Topics, Cool 2009*, pp. 91–93.

[20] Bessonov E. G., Gorbunkov M. V. and Mikhailichenko A. A., *Phys. Rev. ST Accel. Beams*, **11** (2008) 011302.

[21] Mikhailichenko A. A. and Zolotorev M. S., *Phys. Rev. Lett.*, **71** (1993) 4146.

[22] Zholents A. A., Zolotorev M. S. and Wan W., *Phys. Rev. ST Accel. Beams*, **4** (2001) 031001.

[23] Franklin W. A., *Optical stochastic cooling proof-of-principle experiment*, in *Proceedings of PAC07* 2007, pp. 1904–1906.

[24] Paschotta R., *Encyclopedia of laser physics and technology. finesse, cavity, resonator*, `http://www.rp-photonics.com/supermirrors.html`.

[25] Dobiasch P., Meystre P. and Scully M. O., *IEEE J. Quantum Electron. Q*, **E19** (1983) 1812.

[26] Colella R. and Luccio A., *Opt. Commun.*, **50** (1984) 41.

[27] Huang Z. and Ruth R. D., *Phys. Rev. Lett.*, **96** (2006) 144801, slac-Pub-11598; See also: `http://Arxiv.Org/Abs/Physics/0602076v1`.

[28] Tatchin R., *Optical cavity vs. electron beam requirements for the operation of a 1.5 lcls in a regenerative amplifiermode*, slac-Pub-95-7036 (1995).

[29] Kim K.-J., Shvydko Y. and Reiche S., *Phys. Rev. Lett.*, **100** (2008) 2244802.

[30] Kim K.-J. and Shvydko Y., *Phys. Rev. ST Accel. Beams*, **12** (2009) 030703.

[31] Shvydko Y. V., Stoupin S., Cunsolo A., Said A. H. and Huang X., *Nature Physics*, **6** (2010) 196, `http://www.nature.com/nphys/journal/v6/n3/full/nphys1506.html`.

[32] Gavrilov N. G., Kulipanov G. N., Litvinenko V. N., Pinaev I. V., Popik V. M., Silvestrov I. G., Skrinsky A. N., Sokolov A. S., Vinokurov N. A. and Vobly P. D., *IEEE J. Quantum Electron.*, **27** (1991) 2569.

[33] Alexeev V. I. and Bessonov E. G., *Nucl. Instrum. Methods A*, **282** (1989) 436; *Bull. Lebedev Phys. Inst.*, No. 12 (1987) 43.

[34] Shibata Y., Ishi K., Ono S., Inoue Y., Sasaki S., Ikezawa M., Takahashi T., Matsuyama T., Koboyashi K., Fujita Y. and Bessonov E. G., *Phys. Rev. Lett.*, **78** (1997) 2740.

[35] Arbel M., Abramovich A., Eichenbaum A. L., Gover A., Kleinman H., Pinhasi Y. and Yakover I. M., *Phys. Rev. Lett.*, **86** (2001) 2561.

[36] Deacon D. A. G. and Madey J. M. J., *Phys. Rev. Lett.*, **44** (1980) 449452.

[37] Deacon D. A. G., *Phys. Rep.*, **76** (1981) 349.

[38] Bessonov E. G., *Nucl. Instrum. Methods A*, **282** (1989) 442.

[39] BESSONOV E. G., *A method of harmonic generation in a storage ring based fel*, in *Proceedings of 21st International Free Electron Lasers Conference, Aug. 23-28, 1999, Hamburg, Germany* (1999), pp. II–51–II–52.