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FROM COHERENT HARMONIC GENERATION TO STEADY STATE MICROBUNCHING

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Abstract

Steady state microbunching (SSMB) is an electron storage ring based scheme proposed by Ratner and Chao to generate high average power narrow band coherent radiation with wavelength ranging from THz to EUV. One key step towards opening up the potential of SSMB is the experimental proof of the SSMB principle. In this paper, the SSMB experiment planned and prepared by a recently established collaboration is presented starting from a modified coherent harmonic generation (CHG). Single particle dynamics of microbunching in an electron storage ring are analyzed. Though oriented for CHG and SSMB, some of the effects analyzed are also important in cases like bunch slicing, bunch compression, FEL beam transport lines etc, in which precise longitudinal phase space manipulations are involved. These dynamics together with some SSMB related collective effects are to be investigated on the storage ring MLS in Berlin.

INTRODUCTION

SSMB has been put forward to generate high average power narrow band coherent radiation in an electron storage ring [1]. The idea is by precise longitudinal phase space manipulation, microbunching can form and stay in a steady state each time going through the radiator. Once realized, the high peak power radiation from microbunching and high repetition rate of storage ring combined will lead to a high average power facility. Some applications do need high average power short wavelength radiation, kW level EUV light source for example is urgently needed by the semiconductor industry for lithography.

To promote the study of SSMB, especially the EUV SSMB, an initial collaboration has been established among Tsinghua University and several other institutes [2,3]. One key step towards opening up the potential of SSMB is the experimental verification of the principle. An SSMB proof-of-principle experiment is being planned and prepared by the SSMB collaboration based on the Metrology Light Source (MLS) [4], the radiation source of the German national metrology institute (PTB). From the perspective of experimental realization, SSMB is not an easy task on a ring originally not optimized for it [2]. Instead of doing SSMB at once, the collaboration plans to conduct a CHG or single pass microbunching experiment as the first step to verify some basic ideas of SSMB and study related physics. Transition to true SSMB will be implemented later.

CHG

In a CHG experiment (see e.g. [5]), the electron beam is firstly energy modulated by a pulse laser cooperating with an undulator. A small dispersive section between the modulator and radiator then converts the energy modulation to density modulation and microbunches are formed and radiate coherently at the harmonic or fundamental frequency of the modulation laser in the radiator. Usually the modulator and radiator are placed at the same dispersion free straight section with a chicane realizing the R_{56} needed in between. For a low alpha ring like MLS which is equipped with only one undulator and has no very long straight section, we can use partial or the whole ring to play the role of a chicane. In the case of using partial ring, the undulator is used for energy modulation and a dipole can act as the radiator. When using the whole ring, the same undulator can be used as both the modulator and the radiator. Microbunches are formed one turn after modulation and radiate coherently at the modulation wavelength traversing the undulator.

The schematic layouts of using partial and the whole ring to do CHG are shown in Fig. 1. They look similar to the usual CHG experiment, but more details are involved. We can use them to study the interesting single particle dynamics and collective effects related to the formation and maintenance of microbunching in an electron storage ring and this is actually the main motivation of starting the study of SSMB physics from a modified CHG.

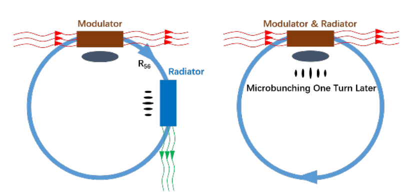

Figure 1: Schematic layout of CHG using partial ring (left) and the whole ring (right).

SSMB

With physics of short term microbunching in an electron storage ring explored in the CHG experiment, the further step would be replacing the pulse laser by a CW laser for a transition to true SSMB. By implementing a highly stable

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optical cavity, stable microbuckets will be formed by the CW laser and the modulator. To maintain a microbunch in a microbucket, a very low alpha lattice is needed to avoid the smearing of bunch caused by the natural energy spread. With the combination of a low alpha lattice and stably established microbuckets, it can be anticipated steady state microbunching would emerge as a result of longitudinal focusing and radiation damping just like the beam bunching in tradition RF buckets. This is the natural idea of SSMB, a scaling from microwave to optical wavelength range. With a five to six orders of magnitude increase of bunch number, it is expected SSMB can realize a high average current without a need of very high peak current, thus overcoming the low average current limit of the usual low alpha rings.

However, for reasons to be introduced momentarily in the next section and also in [2], low alpha lattice alone is not enough or not easy to push the bunch length to nm level needed for coherent EUV radiation. A longitudinal strong focusing scheme is introduced to suppress the bunch length further. This approach of getting extrem short wavelength SSMB is called longitudinal strong focusing SSMB. The schematic layout of the usual and the longitudinal strong focusing SSMB are shown in Fig. 2. There are also several other SSMB scenarios proposed for different wavelengths of radiation on which we do not focus in this paper. In particular, if a reversible scheme is used, for example, the lattice will not require the condition of low momentum compaction. Interested readers are encouraged to read [6-10].

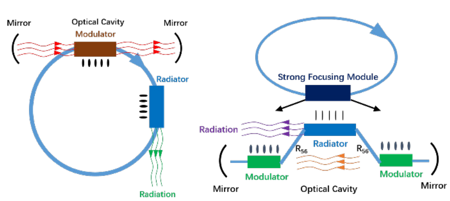

Figure 2: Schematic layout of the usual SSMB (left) and the longitudinal strong focusing SSMB (right).

SINGLE PARTICLE DYNAMICS OF MICROBUNCHING IN AN ELECTRON STORAGE RING

In this section, four single particle effects of microbunching in an electron storage ring are analyzed. These effects are interesting from a beam dynamics viewpoint and some of them play vital roles in the CHG and SSMB experiment. A great part of the experimental goal is to better understand them.

Longitudinal Quantum Radiation Excitation

The conventional way of getting short bunches on an electron storage ring by applying a low alpha lattice is based on the "zero current" bunch length formula

$$\sigma_s = \sigma_{\delta_0}\sqrt{\frac{E_0}{f_0}\frac{\alpha_p}{eV'_{rf}}} \tag{1}$$

with σ_{δ_0} the natural energy spread, E_0 the beam energy, f_0 the revolution frequency, α_p the momentum compaction of the ring, e the elementary charge and V'_{rf} the RF voltage gradient. According to the formula, we can get very short bunches by applying a low alpha lattice and a high RF voltage gradient which is exactly what SSMB is implemented with. But our study shows the relation of $\sigma_s \propto \sqrt{\alpha_p}$ breaks down when α_p is pushed close to zero since quantum excitation need to be considered more carefully. An effect called longitudinal quantum excitation [11] and a parameter called partial momentum compaction factor play a bigger role then. The definition of partial momentum compaction factor is

$$\tilde{\alpha}_p(s_j) = \frac{1}{C_0}\int_{s_j}^{observation}\frac{\eta(s)}{\rho(s)}ds \tag{2}$$

in which s_j and *observation* is the point of photon emission and observation. The physical origin of the longitudinal radiation excitation is a stochastic fluctuation of where the photo emission takes place cooperates with the fluctuation of partial momentum compaction factor produces a fluctuation of path length of one revolution, resulting in a heating effect on the longitudinal coordinate apart from the usual energy heating in the treatment of quantum excitation.

The one turn smearing of longitudinal coordinate is proportional to the one turn induced energy spread times the fluctuation of the partial momentum compaction factor

$$\sigma_{s,one\ turn} \propto \sqrt{I_{\alpha_p}}\sqrt{< Nu^2 >}/E_0 \propto \sqrt{I_{\alpha_p}}E_0^{2.5} \tag{3}$$

where I_{α_p} is the variance of partial momentum compaction factor. For steady state, this effect gives a bunch length limit determined only by lattice optics and beam energy [11]

$$\sigma_{s,lre} = \frac{1}{f_0}\sigma_{\delta_0}\sqrt{I_{\alpha_p}} \propto \sqrt{I_{\alpha_p}}E_0 \tag{4}$$

When we push the bunch length to this limit, the energy spread will increase significantly since the RF will convert the noise of longitudinal coordinate to energy spread.

Some numerical calculations using SLIM [12] and particle tracking using Elegant [13] of the MLS lattice have been conducted to verify the influence of this effect and the scaling law. Due to the space limited, we do not present the results in detail. Interested readers may further refer to [14]. Here we just give some numbers to let the reader have a more concrete feeling of this effect. The one turn smearing of longitudinal coordinate is about 260 nm (rms) when operated at 630 MeV low alpha mode and the corresponding steady state bunch length limit is about 36 µm [15]. The longitudinal radiation excitation should be treated carefully in CHG and SSMB in which micro-structures of µm level or shorter are involved. Lower operation energy is preferred as long as the resonant condition can be fulfilled for the target radiation wavelength and intra-beam scattering is not severe, especially for the case of CHG since it has a more sensitive energy scaling law. Apart from the beam energy, what more important is the dedicated lattice design to suppress the

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fluctuation of partial momentum compaction factor. Some methods to proceed and preliminary lattice design to realize short wavelength SSMB have been presented in [2,16].

First Order Transverse Longitudinal Coupling

The first order transverse longitudinal coupling in a storage ring is a result of the unavoidable dispersion. Under the condition the coupling is not very strong which means the Courant-Synder parameters are still well defined, the longitudinal displacement of a particle relative to the reference particle due to betatron oscillation is [17-20]

$$\begin{aligned}\Delta z &= R_{51}x + R_{52}x' \qquad (5)\\ &=\sqrt{\varepsilon_{CSI}}\left[\sqrt{H_1}\sin(\varphi_{\beta_1}-\varphi_{H_1})-\sqrt{H_2}\sin(\varphi_{\beta_1}+\mu-\varphi_{H_1})\right]\end{aligned}$$

with ε_{CSI}, φ_β the horizontal Courant-Synder invariant and betatron phase, μ and L the betatron phase advance and distance from point 1 to point 2, H and φ_H the chromatic invariant and the chromatic phase.

Note however Eq. 5 assumes we start with a matched betatron oscillation. The situation becomes more involved when there is a sudden change of particle momentum, caused by quantum excitation or energy modulation for example, at a dispersive location since it will then induce a sudden change of dispersive close orbit and betatron motion at the same time. The longitudinal displacement for a particle whose relative momentum deviation δ is caused by a sudden change at the starting point can be expressed as [20,21]

$$\begin{aligned}\Delta z =&\sqrt{\varepsilon_{CSI}}\left[\sqrt{H_1}\sin(\varphi_{\beta_1}-\varphi_{H_1})-\sqrt{H_2}\sin(\varphi_{\beta_1}+\mu-\varphi_{H_1})\right]\\ &-\left[\sqrt{H_1H_2}\sin(\varphi_{H_1}+\mu-\varphi_{H_2})+\alpha_p L\right]\delta \qquad (6)\end{aligned}$$

with α_p the momentum compaction factor from point 1 to 2.

Now we can use Eq. 6 to investigate the influence of the first order transverse longitudinal coupling effect on microbunching. Actually Eq. 6 can also be used to explain the bunch slicing experiment results of Shimada et al [22], but here we focus on its application to CHG and SSMB. The easiest way to avoid the coupling is to let $H_1 = H_2 = 0$ which means the modulator and radiator are placed at dispersion free locations ($\eta = \eta' = 0$), otherwise since different particles have different betatron amplitudes and phases, we need $H_2 = H_1$ and $\varphi_{H_2} = \varphi_{H_1} + \mu$ fulfilled at the same time [20] which would need dedicated tuning of lattice optics and may not be easy for a ring not optimized for this purpose. This effect also gives another bunch length limit of $\sqrt{\varepsilon_x H}$ for the steady state, in which ε_x is the horizontal emittance. The total bunch length is

$$\sigma_s = \sqrt{\sigma_{s0}^2 + \varepsilon_x H} \qquad (7)$$

in which σ_{s0} is the bunch length calculated without considering this effect. Using the MLS lattice as an example, $\sqrt{\varepsilon_x H}$ can be as large as several hundred µm at most dispersive locations when operated at 630 MeV low alpha mode. For both CHG and SSMB we need to avoid the smearing of microbunching caused by this coupling. On the other hand, we can also study the coupling dynamics by modulating the electron beam at a dispersive location on purpose.

Second Order Transverse Longitudinal Coupling

The second order transverse longitudinal coupling effect originates from a dependence of path length on betatron amplitude. A simple quantitative relation of the path length difference relative to the reference orbit can be arrived at as a result of symplecticity [23-27]

$$\Delta C = -2\pi(J_x\xi_x + J_y\xi_y) \qquad (8)$$

in which $J_{x,y}$ and $\xi_{x,y}$ are the horizontal (vertical) betatron action and chromaticity.

This effect is important for free electron laser in X-ray regime since it will smear the microbunching as the beam propagates in the undulator, resulting in a strict requirement on the beam emittance. Methods to overcome this influence are called "beam conditioning" and many have been proposed since the first paper of Sessler et al [28]. The basic idea of these proposals is to compensate the difference of path length through the difference of speed by establishing a correlation between the betatron amplitude and energy.

In a storage ring, unlike in a linac, the correlation of betatron amplitude and energy is an automatic result of longitudinal focusing since the RF always makes all the particles synchronize with it in an average sense. Two experiments [29,30] were conducted by previous authors to verify Eq. 8. However, the influence of this effect on the steady state beam parameters in an electron storage ring has not been investigated until recent experiments conducted on MLS. The quantitative measurements show that this effect will broaden the energy spread and deviate the beam from Gaussian in both horizontal and longitudinal dimensions in a low alpha ring with nonzero horizontal chromaticity. More details about the analysis of this effect and the experiment will be presented in a separate paper [31].

Nonlinear Momentum Compaction

Momentum compaction factor of a ring is actually a function of the relative momentum deviation $\delta = \Delta p/p_0$

$$\alpha_p(\delta) = \alpha_0 + \alpha_1\delta + \alpha_2\delta^2 + \ldots \qquad (9)$$

When α_p is lowered to a very small value, the higher order terms of Eq. 9 will play a bigger role and may shrink the bucket size [32]. Sextupoles and octupoles should be used to adjust α_1 and α_2 to maintain a high enough bucket and a long enough quantum life time.

SUMMARY

The preparation of experimental realization of SSMB starting from a modified CHG is presented. Several interesting single particle effects of microbunching in an electron storage ring are analyzed. These effects together with some SSMB related collective effects are planned to be investigated on the low alpha storage ring MLS.

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