Stochastic Cooling Enhanced Steady-State Microbunching

Authors: Xiujie Deng, Xiujie Deng

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Abstract

In this paper, we propose to combine two promising research topics in accelerator physics, i.e., optical stochastic cooling (OSC) and steady-state microbunching (SSMB). Our study shows that such an OSC-SSMB storage ring with a circumference of 50 m and beam energy of several hundred MeVs using present technology can deliver kilowatt radiation at 100 nm wavelength. A more ambitious application of OSC in an SSMB ring can push the radiation wavelength to an even shorter wavelength, such as EUV and soft X-ray. Such a powerful compact light source could benefit fundamental science research and industry applications.

Full Text

Preamble

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Xiujie Deng∗, Institute for Advanced Study, Tsinghua University, Beijing, China

∗dengxiujie@mail.tsinghua.edu.cn
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Abstract

In this paper, we propose to combine two promising research topics in accelerator physics: optical stochastic cooling (OSC) and steady-state microbunching (SSMB). Our study shows that such an OSC-SSMB storage ring with a circumference of 50 m and beam energy of several hundred MeV using present technology can deliver kilowatt-level radiation at 100 nm wavelength. A more ambitious application of OSC in an SSMB ring can push the radiation wavelength to even shorter wavelengths, such as EUV and soft X-ray. Such a powerful

compact light source could benefit fundamental science research and industry applications.

Introduction

Steady-state microbunching (SSMB) [1–3] scales the bunching mechanism in a storage ring from the conventional microwave or radio-frequency (RF) region to optical wavelengths to generate ultrashort electron bunches on a turn-by-turn basis for high-power short-wavelength coherent radiation generation, and its proof-of-principle experiment has been successfully conducted recently at the MLS storage ring [4, 5]. Optical stochastic cooling (OSC) [6, 7] is a scaling of the conventional stochastic cooling scenario from the microwave to optical frequency range to speed up the damping of particle beam emittance. Its mechanism has also been demonstrated recently in the IOTA storage ring [8, 9]. One interesting idea is then to combine them, which hopefully can relax the technical requirements and enhance the capabilities of an SSMB radiation source.

SSMB Scenarios

SSMB is a general concept and there are several specific scenarios for its realization. Here we group these scenarios into two categories: globally microbunching schemes and locally microbunching schemes.

Globally Microbunching / Longitudinal Focusing

For globally microbunching or longitudinal focusing schemes, the electron beam is microbunched all around the ring. Generally, these SSMB schemes require the storage ring to work in a quasi-isochronous or low-alpha mode. The laser modulators are used in a way similar to that of RF cavities in a conventional storage ring, i.e., to longitudinally focus the electron beam to make it become microbunched. The microbunches are thus separated by a distance equal to the modulation laser wavelength. Note that due to the impact of local phase slippage factor and transverse-longitudinal coupling [2], the microbunch length can vary significantly around the ring. The microbunching here therefore more accurately refers to microbunching in phase space.

Depending on the strength and mechanism of longitudinal focusing, we have developed three such SSMB scenarios in recent years: longitudinal weak focusing (LWF), longitudinal strong focusing (LSF), and generalized longitudinal strong focusing (GLSF) [10, 11], as schematically shown in Fig. 1. For a comprehensive analysis of their beam physics, readers can refer to Ref. [11].

For globally microbunching schemes, the key is to realize a small equilibrium beam emittance. At least one of the three eigen emittances should be ultra-low to realize ultra-short electron bunches with a mild requirement on the modulation laser power. For LWF and LSF SSMB, it is the longitudinal emittance, while for GLSF SSMB it is the vertical emittance.

Locally Microbunching / Reversible Modulation

For locally microbunching schemes, microbunching appears only in a limited section of a storage ring. Outside that limited region, the electron beam is just a conventional bunch, which means it can be an RF bunch or even a coasting beam. A representative method to realize local microbunching is using a downstream reverse laser modulation to cancel the modulation imprinted by an upstream laser modulator, with microbunching appearing only at the radiator in between [12, 13]. By invoking such a reversible modulation scheme, the storage ring does not need to be quasi-isochronous. Depending on the laser-induced microbunching technique—for example HGHG [14], EEHG [15], or PEHG/ADM [16, 17]—we can have HGHG SSMB, Echo SSMB, or PEHG/ADM SSMB, as shown in Fig. 2.

The key to reversible microbunching is to achieve perfect modulation cancellation such that the equilibrium beam parameters can be preserved and the microbunching process can repeat turn-by-turn. However, in reality, due to various physical effects, the modulation cancellation cannot be perfect. One critical issue is the longitudinal coordinate deviation of a particle Δ from its ideal location between the upstream laser modulator and downstream reverse laser modulator, described by $\{\sin[\ (\ +\Delta\ )] - \sin(\ )\}$, with the laser wavenumber and the energy chirp strength around zero-crossing phase. The sources of Δ include effects like quantum excitation, intrabeam scattering (IBS), coherent radiation, linear optics mismatch, and lattice nonlinearities [13]. Non-perfect cancellation results in growth of the energy spread, and when $|\Delta\ |$, we have $\Delta\ ^2 = (\ \Delta\ )^2/2$. If the modulators are placed at dispersive locations, as in PEHG/ADM SSMB, this also leads to growth of transverse emittance.

For HGHG and Echo SSMB, the key parameter is the energy spread, while for PEHG/ADM SSMB, it is the vertical emittance. Growth of these parameters means the required modulation laser power will be even higher to achieve a given coherent radiation wavelength. Our analysis has revealed a universal criterion for the tolerance of the rms value of Δ [13]:

$$\Delta \qquad /2 \quad ,\mathrm{damp}$$

where is the target radiation wavelength and ,damp is the longitudinal damping time in units of revolution numbers.

Motivation of a Faster Damping

A faster damping rate in an SSMB storage ring can help obtain a smaller equilibrium beam emittance and energy spread, increase the tolerance of non-perfect modulation cancellation, and counteract collective effects. This can mitigate technical challenges and enhance the potential of an SSMB source. While a damping wiggler seems to be a straightforward choice to enhance damping, an OSC section has the advantage of a more compact setup and higher efficiency in converting wall-plug electricity to user-desired radiation.

OSC Basics

After a brief introduction of SSMB, we present some basics of OSC to make our paper more self-contained.

Cooling Mechanism and Damping Rate

The cooling mechanism of an OSC section is to use each electron’ s radiation generated in the pick-up undulator to correct its own momentum deviation in the kicker undulator. The kicks from nearby electrons’ radiations within the radiation slippage length constitute a heating effect. Assume that the corrective energy kick due to each particle’ s own radiation is given by:

$$\Delta \quad = - \quad \sin(\quad \Delta \quad)$$

If $\Delta \quad = \quad {}_{56}$ with ${}_{56}$ the momentum compaction between the pick-up and kicker undulator, then the longitudinal damping rate is:

$$\alpha \quad = \quad {}_{56}/2$$

For analysis of damping rates in a general coupled lattice, readers can refer to Ref. [18]. Considering the sinusoidal waveform of the kick, the damping rate is actually amplitude-dependent, and to ensure damping for the majority of the particle beam, we need a sufficient cooling range [9].

Bandwidth Limit

The bandwidth of an OSC section is limited by the ability to identify each electron, which is determined by the OSC undulator radiation slippage length . So = / , with and the OSC undulator radiation frequency and period number, respectively. Assuming perfect mixing and an appropriate amplifier, the theoretical optimal damping rate is 1/ , with the total number of particles in the ring. For a coasting beam, we have the optimal damping time in units of revolutions:

$$= \ / \ {}_{,\text{damp,opt}} = \text{No. of } \quad \text{in the OSC radiation slippage}$$

To achieve fast damping in OSC, a short radiation slippage length is required. In this sense, a shorter OSC undulator radiation wavelength is desired, for example EUV [19].

Mixing Condition

A central problem in stochastic cooling is mixing. Loosely, good mixing means the particles in the OSC radiation slippage length update turn-by-turn. More accurately, it means the overlap of particles’ Schottky bands in the feedback system bandwidth. Since reversible SSMB scenarios do not require a small momentum compaction for the ring, the mixing condition can be straightforwardly satisfied in these schemes, as long as we have $| \quad {}_0|$, with the beam energy spread, the phase slippage factor, and ${}_0$ the circumference of the ring.

In this paper we only discuss the application of OSC in a reversible SSMB ring. The mixing condition in globally microbunching schemes is more subtle, and the combination of these schemes with OSC will be reported elsewhere in the future.

Radiation Kick Strength

The OSC radiation kick strength in Eq. (3) is determined by the details of the pick-up, kicker, optical system, and amplifier if present. Assuming identical pick-up and kicker planar undulators, a refractive optical system, and a perfect linear amplifier, the radiation kick strength is [9]:

$$= (\gamma\ )^2/3\gamma\ \ ^2 \times 2\ [\ ]\ (\ ,\gamma\ )$$

with the angular acceptance of the focusing lens, the radiation power amplification factor, and for $0 \leq\ \ \leq 4$ we have $(\ ,\infty)\ \ 1/(1 + 1.13\ ^2 + 0.04\ ^3 + 0.37\ ^4)$.

Equilibrium Energy Spread

If we consider the combined effects of OSC, radiation damping, quantum excitation, and other diffusion-like effects, the equilibrium energy spread is given by:

$$= \surd[(\ \ \ + \Delta\ ^2 ,\ \ + \Delta\ ^2 ,\ )/(\alpha\ \ + \alpha\ \ )]$$

where $\Delta\ ^2 ,\ \ = \ ^2/$ is the heating effect of nearby particles' radiation kicks in the OSC, $\Delta\ ^2 ,\ \ = 4\alpha\ \ ^2\ _0$ is the natural quantum excitation with $_0$ the natural energy spread and α the longitudinal radiation damping rate, and $\Delta\ ^2 ,$ is from other energy spread growth effects, for example that due to non-perfect cancellation in a reversible SSMB ring. With other parameters fixed, there is an optimal that minimizes the equilibrium energy spread.

Combine OSC with Reversible SSMB

Schematic Setup and Parameters List

Now we use the application of OSC in a reversible HGHG SSMB ring to increase the longitudinal damping rate as an example to demonstrate the benefit of implementing OSC in an SSMB storage ring. A schematic layout of such an OSC-HGHG-SSMB storage ring is shown in Fig. 3, and an example parameter list is given in Tab. 1. In this example, the desired radiation wavelength is assumed to be the 8th harmonic of the modulation laser, i.e., = 100 nm with = 800 nm. The envisioned ring consists of two arcs and two straight sections. The circumference of such a ring is about 50 m. The two straights are about 2 × 15 m, and the two arcs are about 2 × 10 m. The OSC section is implemented in one straight section, while the other is used for HGHG and reverse HGHG. The average modulation laser power is set to be 1 MW, which is close to the state-of-the-art value reachable in an optical enhancement cavity [20]. All the parameters in Tab. 1 should be feasible from a practical viewpoint.

Induction Linac and Barrier Bucket

To mitigate collective effects like IBS, the peak current we apply is not too high, namely 1 A. However, for high-average-power output radiation, we hope for a high average beam current. Therefore, we may use an induction linac as the energy compensation system to obtain a coasting beam with a large filling factor, for example 50% in the ring. Assuming the repetition rate of the induction linac is the same as the particle revolution frequency in the ring, which is 6 MHz, the acceleration voltage cc 2 kV, considering that the incoherent radiation loss in dipoles and coherent radiation loss in the radiator undulator are each about 1 keV per electron. To form the barrier bucket, we let the acceleration voltage have two edge slopes as shown in Fig. 4. The barrier bucket half-height formed by these two slopes is:

$$\Delta \ = \surd(\ _0/\ _0) \times (\Delta\ /\ \ )$$

with $_0$ and Δ the magnitude and time duration of the slope. If $_0 = 300$ MeV, $_0 = 50$ m, $= 1 \times 10^{-3}$, Δ = 20 ns, then to realize a bucket half-height of Δ = 0.02, which means about 100 given in the table, we need $_0 = 1$ kV. Such a requirement on the induction linac should be feasible. We point out that it is also possible to realize a large beam filling factor by using a combination of different RF harmonic cavities to lengthen the RF bunch in an RF bucket.

Intrabeam Scattering

To minimize the IBS diffusion rate, we have used a transversely round electron beam, with a large transverse emittance of = 6 nm. The IBS diffusion of energy spread for a transversely round beam (=) is [21]:

$$1/\ \ ,\mathrm{IBS}\quad (8\ \gamma^{3\ 2}\ \ \Psi_0\qquad)/(\qquad)$$

where Ψ_0 is a constant depending on the lattice optics around the ring. Here for an order-of-magnitude estimation, we put in some numbers: $\Psi_0 = 1$, Coulomb Log = 10, average transverse beam size around the ring = √(6 nm × 10 m) 250 m, $= 1.9 \times 10^{-4}$, = 1 A, we have ,IBS = 169 ms, which is more than one order of magnitude longer than the OSC damping time. For the transverse dimension, ,IBS = ,IBS/ . When 0.2 m, it is acceptable for the transverse dimensions.

Coherent Undulator Radiation

The radiator is assumed to be an undulator. The radiation power at the fundamental resonance frequency from a transversely round electron beam in a planar undulator is [2]:

$$[\mathrm{kW}] = 1.183\ \ [\ \ ]^2\ \ (\ )|\ \_z|^2\ \ ^2[\mathrm{A}]$$

where $[\ ]^2 = [\ _0(\ ) - \ _1(\ )]^2$, with $= \ ^2/(4 + 2\ ^2)$ and being the undulator parameter, and the transverse form factor is $(\ ) = 2[(2\ )^2/((2\ )^2 + 1) + \tan^{-1}(1/(2\ ))]$, with $= \ /(4\ \ ^2)$ being the diffraction parameter and the rms transverse electron beam size, _z is the bunching factor at the radiation wavelength, and is the peak current. For the radiation power of a helical undulator, there is no $[\ ]^2$ factor and the power can roughly be about a factor of 2 larger. The power given in the table assumes a helical undulator radiator. Similarly, we can also use a helical undulator as the modulator to lower the required modulation power by a factor of 2 compared to a planar undulator.

Remaining Issues

While feasible in principle, there are important issues to be resolved before such an OSC-HGHG-SSMB ring becomes a reality. For example, is the required amplifier for OSC radiation available at such short wavelengths? We recognize that we may also perform OSC without an amplifier. Is it challenging to realize the required phase-locking of electrons and their own radiation in OSC, especially when we want to shorten the radiation wavelength to increase the bandwidth for faster damping? How can we realize the phase locking of the two optical cavities, or more accurately, the locking of the downstream laser modulator to the electron beam arrival time to ensure perfect modulation cancellation?

Summary

Both OSC and SSMB have great potential, and here we propose to combine them for an even brighter and longer future. The application of OSC in a reversible SSMB ring for a 1 kW, 100 nm radiation source has been presented. Such a compact source (circumference 50 m) can be built in universities and institutes at reasonable cost and would be useful for basic science research. Work on the application of OSC in global microbunching SSMB scenarios is ongoing and will be reported in the future.

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Note: Figure translations are in progress. See original paper for figures.