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Steady State Microbunching for High Brilliance and High Repetition Rate Storage Ring-Based Light Sources

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INTRODUCTION

Electron-based light sources have proven to be effective sources of high brilliance, high frequency radiation. Such sources are typically either linac-Free Electron Laser (FEL) or storage ring types. The linac-FEL type has high brilliance (because the beam is microbunched) but low repetition rate (see e.g. [1]). The storage ring type has high repetition rate (rapid beam circulation) but comparatively low brilliance or coherence. We propose to explore the feasibility of a microbunched beam in a storage ring that promises high repetition rate and high brilliance. The steady-state-micro-bunch (SSMB) beam in storage ring could provide CW sources for THz, EUV, or soft Xrays. Several SSMB mechanisms have been suggested recently, and in this report, we review a number of these SSMB concepts as promising directions for high brilliance, high repetition rate light sources of the future [2, 3, 4, 5].

The trick of SSMB lies in the RF system, together with the associated synchrotron beam dynamics, of the storage ring. Considering various different RF arrangements, there could be considered a number of scenarios of the SSMB. In this report, we arrange these scenarios more or less in order of the envisioned degree of technical challenge to the RF system, and not in the chronological order of their original references.

Once the stored beam is steady-state microbunched in a storage ring, it passes through a radiator repeatedly every turn (or few turns). The radiator extracts a small fraction of the beam energy as coherent radiation with a wavelength corresponding to the microbunched period of the beam. In contrast to an FEL, this radiator is not needed to generate the microbunching (as required e.g. by SASE FELs or seeded FELs), so the radiator can be comparatively simple and short.

CONVENTIONAL MICROWAVE RF SYSTEM

The simplest SSMB mechanism is the well-known conventional technique of shortening the steady state bunch length by raising the voltage of the RF system. Choosing a higher RF frequency, e.g. to X-band, also helps. Another way not involving RF is to introduce a small momentum compaction factor by the lattice design of the storage ring [6, 7]. Once the steady bunch length is reduced, this simplest SSMB scenario has been suggested to produce THz radiation.

This conventional SSMB scenario can be pushed further by combining the above-mentioned effects (higher RF voltage, higher RF frequency, and low momentum compaction factor). By pushing all three fronts simultaneously, a very short steady state bunch length can be reached [2].

Taking the SPEAR3 storage ring as an example, it was suggested by [2] to reduce the bunch length from 5 mm of the regular user operation mode to 0.3 mm, using a combination of reducing the momentum compaction factor α_p by a factor of 20 from the nominal value together with an application of X-band RF modulation of 7.6 MV applied every 4 turns. This scheme for THz generation has the advantage that it does not impose excessive demand on the usual microwave instability and the coherent synchrotron radiation effects.

LONGITUDINAL BETA BEAT

Pushing the conventional scenario to an extreme with much higher RF voltage and moving towards X-band RF frequency, an additional longitudinal beta-beat effect further shortens the bunch length [2].

We now consider the case when the RF is lumped at one location around the ring. We define the parameter

$$K = \frac{2eV_{mod}\alpha_p C}{E_0\lambda_{mod}} \tag{1}$$

where C is the storage ring circumference, E_0 is the electron energy, V_{mod} and λ_{mod} are the voltage and wavelength of the RF modulation. Conventionally storage rings have $K \ll 1$, synchrotron oscillation is slow and the synchrotron tune is $\ll 1$. By contrast, in this scenario, K is on the level of 1 and with a localized RF system, it can be shown that the steady state bunch becomes unstable at the origin of phase space when $K > 4$.

Increasing K towards 4, the Courant-Snyder formalism can be used to describe the longitudinal synchrotron motion and electron phase space. The periodic longitudinal beta function β_z beats around the ring, and when K approaches 4, this beat becomes large, with the minimum beta occurring at the location diagonally opposite to the RF (assuming evenly distributed α_p). By locating the radiator at the minimum beta, the bunch gets shorter by an additional factor of $\sqrt{\beta_z}$.This scenario helps shortening a bunch further into the THz range.

The longitudinal beta-function is given by

$$\beta_z = \beta_{max} = \frac{2\alpha_p C}{\sqrt{K(4-K)}} \qquad \text{at modulator RF}$$

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$$\beta_z = \beta_{min} = \frac{\alpha_p C}{2}\sqrt{\frac{(4-K)}{K}} \quad \text{opposite modulator RF} \tag{2}$$

Note that this Courant-Snyder linear analysis breaks down when bunch length at β_{max} becomes a significant fraction of λ_{mod}.

The method described above requires high RF frequencies. An alternative approach is to use a lower frequency, but pulse the RF once every N_{turn} turns. In this case, α_p effectively becomes N_{turn} times larger and K increases accordingly. In this scenario, it may be necessary to keep a separate lower-frequency RF system (or a barrier RF) to produce bunching buckets to confine particle motion.

BUCKET BIFURCATION

Further shortening of the steady-state bunch length occurs beyond the stability limit $K = 4$, when the RF bucket becomes unstable at the phase space origin. At $K > 4$, the RF bucket bifurcates into two small buckets as shown in Fig. 1 [3]. By choosing $K > 4$ but close to 4, the two small buckets can be much smaller than the original RF bucket before bifurcation. Furthermore, placement of the radiator relative to the RF module controls the spacing between the two bunchlets. Parameters can then be chosen so that the two bunchlets radiate coherently at a wavelength equal to the spacing between the two bunchlets. In addition to microbunching the beam, a bifurcated beam can be useful particularly for pump-probe applications.

The SSMB based on bucket bifurcation is named period-2 SSMB. Taking SPEAR3 storage ring as an example, we have illustrated the feasibility of period-2 SSMB to generate coherent THz radiation using an X-band RF system in pulsed operation mode [3].

STAGGERED BUCKET SSMB

The staggered bucket SSMB was chronologically the first concept proposed [4]. To reach short wavelengths, it is in principle possible to replace the RF buckets with a shorter wavelength modulation, e.g. by a laser at IR to UV frequencies. For this short wavelength bucketing system, a radiation source co-propagating with the beam in an undulator applies the bucketing voltage.

As the bucketing frequency increases, the steady state bunch length naturally decreases according to the conventional mechanism. This SSMB scenario is considered already earlier as part of the conventional scenario. However, sufficiently high modulation frequencies make possible a new mechanism which invokes a configuration of staggered buckets in longitudinal phase space.

When the bucketing laser frequency is high enough, the momentum acceptance of the storage ring can accommodate multiple staggered RF buckets in momentum space (see Fig. 2). The nominal buckets will be a string of buckets spaced by the laser wavelength. (The K value of each bucket can be flexible and does not have to be close to or larger than 4.) However, additional strings of buckets above and below the nominal string are now possible in which each bucket shifts by an integral multiple of the laser wavelength per revolution of the beam. With a very short bunching laser wavelength, λ, it is now possible that these additional buckets, staggered above and below the nominal energy, appear in the phase space. If the momentum aperture of the storage ring is large enough, the number of staggered buckets strings, M, can be large. For example, if we take a laser of approximately $\lambda = 1\,\mu$m, we could have $M > 10$.

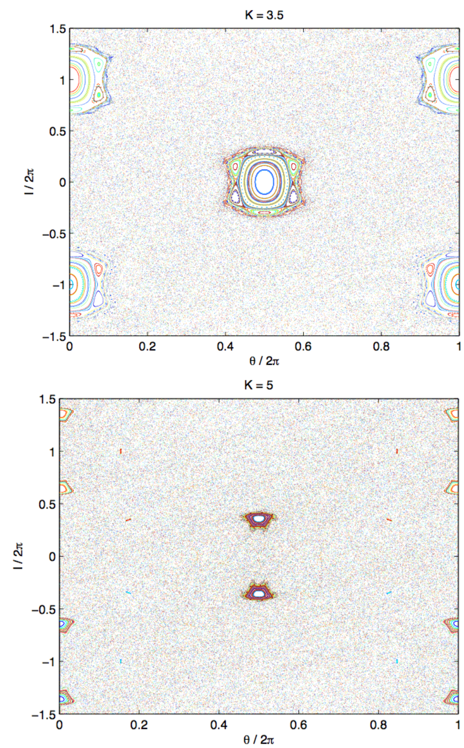

Figure 1: The particle distribution in longitudinal phase space with K = 3.5 (upper) and 5 (lower).

By locating a radiator a certain distance downstream from the laser modulator, the M strings slip in their relative longitudinal positions in such a way that the beam now has split into M bunchlets evenly spaced by a distance of λ/M and a harmonic generation of a factor of M is reached. With sufficiently large M, this scenario may be considered to induce coherent radiation approaching the EUV lithography wavelength [4]. An example schematic is given in Fig. 3. Note that by moving the radiator closer to the modulator, it is possible to reach harmonics greater than M, though bunchlets will not fill ever harmonic bucket.

FREQUENCY BEATING SSMB

A variation of the staggered scenario occurs when the laser modulator is replaced by two modulations of nearly equal wavelength, $\lambda_1 = \frac{b}{b-1}\lambda_2$, so that the beam is mi-

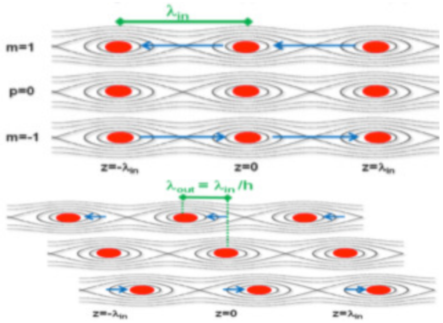

Figure 2: Staggered buckets as viewed at the modulation point (upper), and as viewed 1/3 around the ring ($M = 3$) (lower). The projected beam distribution at the 1/3-location is microbunched at the 3rd harmonic of the modulation frequency.

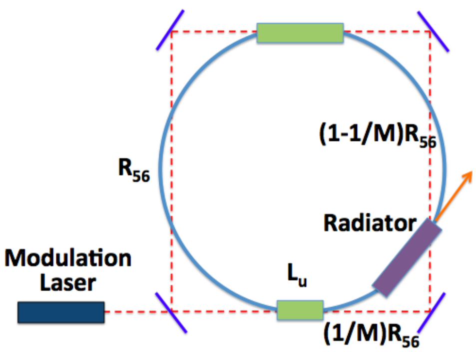

Figure 3: Example schematic for a two-modulation version of staggered bucket SSMB. A laser cavity and two undulators of length L_u and $1.9L_u$ modulate the electron beam at opposite ends of a storage ring. SSMB from the modulation and dispersion produces coherent light in a radiator. RF modules could replace the laser modulation to produce long wavelengths.

crobunched at the beat wavelength $\lambda_{\rm SSMB} = b\lambda_2$ [4]. The steady state beam will have SSMB spacing equal to the beat wavelength, which is much longer than either seed wavelength. (We note that frequency beating has been proposed previously for linacs [8].) Frequency beating can then produce SSMB bunches of moderate wavelengths such as in the THz regime , which is otherwise not easily accessible with extrapolations using conventional means. Note that only one undulator is needed for the modulations if the two wavelengths are contained within the undulator bandwidth.

REVERSIBLE SEEDING SSMB

Seeding can also be considered in a SSMB scheme. For example, High Gain Harmonic Generation (HGHG) [9], Echo-Enabled Harmonic Generation (EEHG) [10] and sawtooth seeding [11, 12] have all been proposed and/or demonstrated for standard linac-driven FELs. Another possible SSMB scenario would use a seeding scheme inside the ring, followed by another reversed system to return the microbunched beam back to its normal Gaussian phase space distribution [5]. Figure 4 presents a schematic of this scheme. In a conventional storage ring, after seeding the electron bunch must circulate many times until radiation damping returns the beam to its initial state. As a result, the radiation source repetition rate is much lower than the circulation rate. By inserting a reversal stage, the beam returns to its initial state immediately following the radiator and can be reused on its next turn. Note that this will typically require dispersive sections of opposite signs or insertion of I transformation in the betatron lattice. Reversible SSMB can radiate coherently at the insertion wavelength, but with storage ring repetition rates. Though conceptually simple, the reversible scheme does require tight tolerances to recover the original energy spread of the beam.

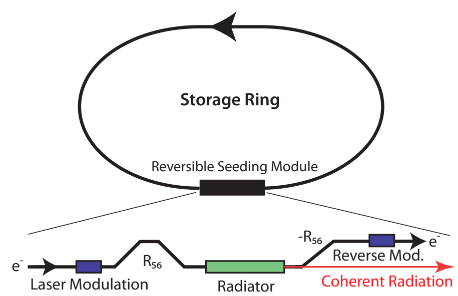

Figure 4: Schematic of the reversible HGHG scheme. A modulation and dispersive region produce microbunching according to the HGHG process. A radiator then extracts coherent radiation at a high harmonic of the seed wavelength, before an opposite sign dispersive region and second modulation reverse the HGHG process and return the beam to its original state.

ADDITIONAL COMMENTS

Unlike linac-based FELs, particles circulating in the storage ring in the SSMB scheme require stability of particle motion. The very large momentum modulation required in some of the SSMB schemes will cause transverse deviations through dispersion functions along the ring, and lead to coupling between the longitudinal and transverse motions. If uncorrected, this synchro-betatron coupling effect, in some severe circumferences (e.g., $K > 4$), can cause particle loss and finally affect the SSMB performance. We will next study this critical consideration.

We conclude that SSMB offers in principle a way to combine the high brilliance of linac-based FELs and the high repetition rate of storage-ring-based light sources, and may possibly point a way for the future generation of light sources. Here we presented a few preliminary concepts of SSMB. Needless to say, more development efforts are needed at this early stage.

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