**Abstract**

A recently proposed mechanism of steady-state microbunching (SSMB) in storage rings is challenged to provide a high power radiation source whose wavelength is 13.5 nm in the EUV range appropriate for lithography applications. A seed laser with wavelength of 300 nm is used to provide the microbunching and the longitudinal focusing needed for the microbunches to reach 13.5 nm, the 22-th harmonic of 300 nm. One example design is provided assuming a storage ring similar to the SPEAR ring at SLAC but with a momentum compaction comparable or lower than what it has so far ever reached. The 13.5-nm radiation power targeted in this example is 1 kW, but it is found that, at the required peak current of the microbunches, the coherent synchrotron radiation at the radiator undulator will disrupt the microbunch buckets. The mechanism of staggered buckets is suggested to circumvent this CSR disruption if an existing SPEAR-like storage ring is to be used to reach 1 kW. Otherwise, a dedicated storage ring is expected to allow the flexibility needed to reach the same goal.

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# Applying Steady State Microbunching to a Storage Ring as High Power EUV Radiation Source

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## 1 Motivation

Accelerators have been considered a powerful source of photon radiation for many applications. Storage rings produce synchrotron radiation, while linac-based free electron lasers (FEL) provide bright radiation from IR to hard X-rays. Storage ring synchrotron radiation, however, has the weakness of a relatively low peak power, and pulsed linac FELs have the weakness of low average power due to their low repetition rates.

There have been creative ways to use superconducting linacs [1, 2, 3], energy-recovery linacs [4], or storage rings [5, 6, 7, 8] for FEL applications to address this issue. Recently, it has also been proposed [9] to overcome these weaknesses by invoking a mechanism of steady-state microbunching (SSMB) in a storage ring including the higher harmonic generation to reach the desired short wavelengths. The idea is to manipulate the beam's longitudinal dynamics so that its steady-state distribution is not the conventional Gaussian, but a microbunched state, as schematically illustrated in Fig. 1.

Since it is in steady state, the beam is microbunched every turn. If a radiator (undulator) is inserted, it will radiate every turn. There is not a need to wait a radiation damping time for beam recovery after each radiation passage. As a result, the system can provide a high CW radiation power, especially in a multi-bunch operation of the stored electron beam, due to its high repetition rate. Furthermore, in the radiator, there is no need of a long undulator section to initiate the microbunching as is required in a single-pass FEL – the beam is already microbunched upon entering; a short undulator will suffice. The radiator of this device is not an FEL.

## 2 Staggered Buckets

There are in principle several ways to generate SSMB in a storage ring [9, 10, 11]. For example [9], by using a seed optical laser to energy-modulate the

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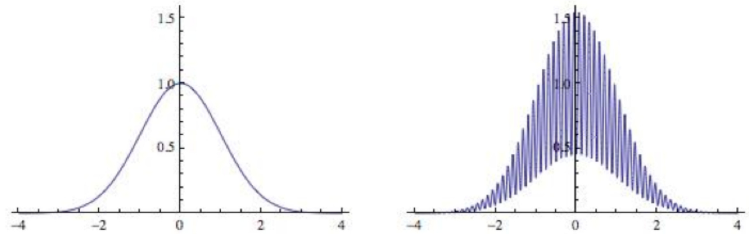

Figure 1: Schematic illustration of a conventional Gaussian beam distribution (left) and a targeted microbunched distrobution (right). A potential well with microbunched structure is superimposed onto the original quadratic potential well that provided the Gaussian beam, so that the new steady-state beam distribution acquires a SSMB structure.

electron beam, a mechanism of staggered buckets was introduced to generate high harmonics of the seed radiation into the EUV range.

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 $\lambda$. However, additional strings of buckets above and below the nominal string are now possible in which each bucket shifts by an integral multiple of $\lambda$ per revolution of the beam. With a very short bunching laser wavelength, it is now possible that these additional buckets, staggered above and below the nominal energy, appear in the phase space. The number of staggered bucket strings $h = 2A_\delta R_{56}/\lambda$, where $\pm A_\delta$ is the momentum aperture of the storage ring.

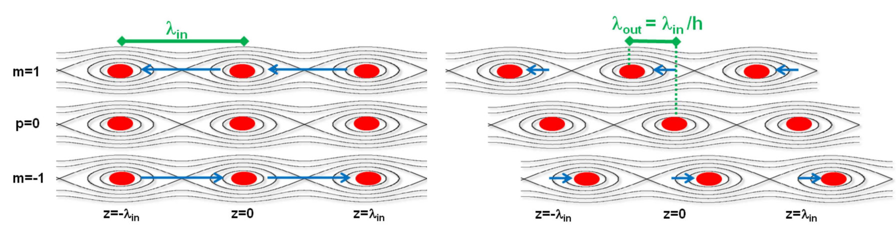


Figure 2: Staggered buckets as viewed at the modulation point (left), and as viewed 1/3 around the ring ($h = 3$) (right). The projected beam distribution at the 1/3-location is microbunched at the 3rd harmonic of the modulation frequency.

By locating a radiator a certain distance downstream from the laser modulator, the $h$ strings slip in their relative longitudinal positions in such a way that the beam now has split into $h$ bunchlets evenly spaced by a distance of $\lambda/h$ and a harmonic generation of a factor of $h$ is reached. With staggered buckets, the intensity per microbunch is reduced by $h$. In case $h$ is large enough, this staggered buckets scenario may be considered to combat the collective effects (more later).

# 3 Outline of Device

In this paper, we apply the SSMB mechanism first without using staggered buckets. Like [9], we induce the optical SSMB mechanism in such a way that the microbunches are pinched (longitudinally focused) at a specific location in the storage ring, but the mechanism of staggered buckets is not used initially. If this electron beam is sent through an undulator resonating with the chosen EUV wavelength at that location, and if the pinched microbunch length there is much shorter than the EUV wavelength, high power CW EUV radiation can be produced. We envision this possible high power EUV source to be suitable for lithography applications.

In Section 4, we describe the envisioned SSMB mechanism induced at a modulator seeded with a 300-nm laser. The modulator strength is intentionally minimized so that its main function is only to modulate the beam energy by a seed laser, and not as a radiator. The energy modulation, together with the ultra-low momentum compaction in the rest of the storage ring, microbunches the electron beam and pinches the microbunches longitudinally. Section 5 is a short discussion of the needed seed laser power. In Section 6, we make a detour with a short discussion of a possibility of spontaneous self-generation of SSMB mechanism without a seed laser, although this self-generation is not considered in the proposed scenario. In Section 7, we then return to our proposal and extend this optical source to become an EUV source by adding another undulator at a position where the bunch length is pinched the shortest, for a 22-nd harmonic radiation at 13.5 nm wavelength. By applying this SSMB to a storage ring with SPEAR-like parameters, we aim for a radiation power of 1 kW. The value of momentum compaction assumed in our example is comparable or lower than the lowest value ever achieved at SPEAR. In Section 8, we discuss the possibility of accommodating higher momentum compaction by splitting the modulator into two synchronized sections. Sections 9 and 10 mention the test proposal for a SPEAR-like ring and what one might consider in a dedicated ring, respectively. Section 11 gives a summary of this study, including a short list of further studies to be made.

Figure 3 is a schematic of the proposed device. Basically all one has to do is to insert two undulators – a modulator undulator and a radiator undulator – in an electron storage ring with a low momentum-compaction lattice. The modulator resonates with 300 nm radiation. The radiation from a seed laser either interacts with the beam in single passes (if the corresponding required seed laser can be provided) or is stored between two mirrors synchronized with the electron beam bunches (to reduce the required seed laser power). The

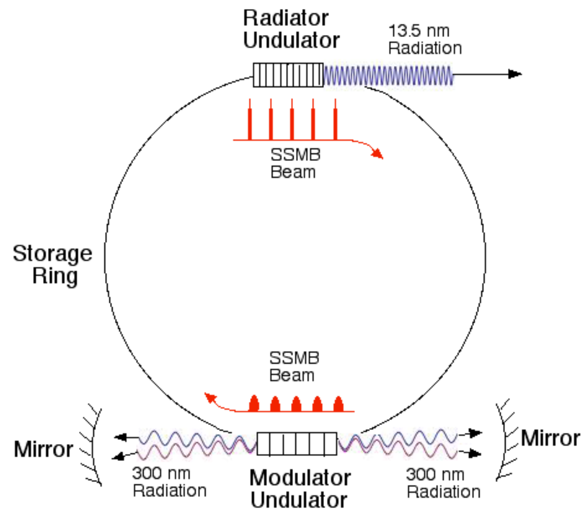


Figure 3: Schematic of the proposed SSMB device. The two mirrors are needed only to reduced the required seed laser power. Otherwise it is to be avoided to minimize any storage ring FEL accumulation.

modulation is weak so that no significant SASE FEL has occurred in single passages. The 300-nm radiation from the electron beam in the modulator is (directed out of the mirrors if mirrors are used) applicable to users or to a dump. Like the radiator, the modulator is also not an FEL.

On the other hand, if mirrors are used, the beam radiation built up between mirrors from spontaneous synchrotron radiation, if not extracted, could provide an easy initiation by self-generating the SSMB process even without a seed laser. An external seeding is needed to impose coherence of the microbunches along the entire length of each electron bunch, but not considered essential for the SSMB mechanism. Without the seed laser, in our example, a self-generated SSMB will still function, but with 9% of the advertised radiation power.

In Fig. 3 is also another undulator illustrated without mirrors. It resonates at 13.5 nm and serves as a simple radiator. The beam generates coherent EUV radiation each time it passes by the radiator. Both undulators are 2.5 m long.

The electron beam consists of many bunches. Illustrated (in red) in Fig. 3 are snapshots of the longitudinal distribution of a short section within a single bunch as it passes by the two undulators. The distribution exhibits microbunched structure within the single bunch. Spacing between the microbunches is 300 nm at both undulator locations. The length of the microbunches, however, are different at the two locations. At the modulator, the rms microbunch length is 75 nm (in order to have a high bunching factor, it must be much shorter than 300 nm). At the radiator, it is strongly pinched by the modulator radiation to 2.52 nm so that it is much shorter than 13.5 nm.

It may be mentioned here that, also suggested in [9], if there are two modulators with nearby frequencies, the microbunching occurring at their beating frequency can in principle be used to lower the radiation frequency to reach THz applications.

# 4 The SSMB Mechanism

In one of the straight sections of the storage ring, we insert the modulator resonant at $\lambda = 300$ nm. The 300-nm radiation from a seed laser is pulsed in synchronization with the electron beam bunches. If the storage ring is nearly isochronous, i.e. if the momentum compaction around the storage ring $R_{56} \approx 0$, a particle's longitudinal distribution does not change much from turn to turn, and microbuckets are formed with multiple passages of the beam through the modulator. With radiation damping, the beam will reach a steady state, in which the electrons become microbunched at 300 nm spacing in coherence with the radiation. This steady state of the electron-radiation system then constitutes the SSMB mechanism. The undulator period length $\lambda_u$ satisfies

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right), \tag{1}$$

with $\gamma mc^2$ the electron beam energy, $K$ the undulator strength parameter.

To find the SSMB steady state of the electron-radiation system, let us assume that a steady state has been established with the laser electric field having a peak value $\hat{E}_0$. As electrons pass through the undulator, copropagating with the optical radiation, it gets energy-modulated with a modulation amplitude

$$e\hat{V} = \frac{e\hat{E}_0 K}{2\gamma} L_u, \tag{2}$$

where $L_u$ is the undulator total length.

This energy modulation (2) together with the momentum compaction $R_{56}$ constitute the longitudinal dynamics of the electron beam's microbunching. Upon radiation damping, the electron beam is regrouped into microbunches, spaced at 300 nm apart. Each microbunch has a bunch center, with neighboring particles executing synchrotron oscillations around it. Linearizing around these bunch centers, the motion of a particle can be analyzed using the standard Courant-Snyder formalism. We obtain the microbunching synchrotron tune $\nu$ and the longitudinal $\beta$-function, $\beta_1$, at the middle of the arc (opposite to the modulator undulator):

$$\begin{aligned}\cos 2\pi\nu &= 1-\frac{R_{56}}{2f}, \\ \beta_1 &= \frac{R_{56}}{\sin 2\pi\nu}(1-\frac{R_{56}}{4f}),\end{aligned} \tag{3}$$

where $\frac{1}{f} = \frac{2\pi e\hat{V}}{E_0\lambda}$.

Energy spread of the electron beam is determined by synchrotron radiation in the storage ring arc and the two undulators. Let the rms relative energy spread at the middle of the arc be $\sigma_{\delta 1}$, then the bunch length there is

$$\sigma_{z1} = \sigma_{\delta 1}\beta_1. \tag{4}$$

In the present example, we assume the storage ring lattice is designed to give $\sigma_{\delta 1} = 3 \times 10^{-4}$. (Our example assumes a SPEAR-like storage ring, whose nominal operation energy is 3 GeV but is operated at 1 GeV. The bare lattice gives $\sigma_{\delta 1} = 2.4 \times 10^{-4}$ at 1 GeV. The two undulators affect both quantum excitation and radiation damping. Taking their incoherent synchrotron radiation into account, and weighting the quantum excitation by thier respective longitudinal $\beta$-functions, the resulting $\sigma_{\delta 1}$ becomes $1.7 \times 10^{-4}$. In this example, we assume $\sigma_{\delta 1} = 3 \times 10^{-4}$.) The rms energy spread in the radiator is the same as in the arc, but inside the modulator it is pinched and becomes $1.01 \times 10^{-5}$ at the center of the modulator. Note that the straight sections of the two undulators are assumed to be dispersion free.

Once $\sigma_{z1}$ and $\sigma_{\delta 1}$ are determined, the microbunch length and relative energy spread at all other locations in the storage ring can be determined. We designate their values at the middle of the modulator by $\sigma_{z2}$ and $\sigma_{\delta 2}$, and the $\beta$-function by $\beta_2$. The longitudinal phase space distribution at various locations around ring is sketched in Fig. 4.

We intend to make the microbunches short at the radiator to be located at the middle of the arc. To do so, we choose $\nu = 0.4893$, close to 0.5, a half-integer resonance. It is common practice in a conventional storage ring that its synchrotron tune is chosen close to the integer 0. Here we choose a similar distance from a half-integer. The challenge will come from a large beating of the longitudinal $\beta$-function. With a good control of the seed laser intensity at the modulator, a beating of $\beta_2/\beta_1 = 884$ is considered in our example design. The parameters we assumed in this example are given in Table 1. In Section 8, we will include a discussion of a possiblility to avoid operating at $\nu \approx \frac{1}{2}$ and the large $\beta$-beat.

With radiation at wavelength $\lambda$, the microbunched beam has a bunching factor

$$B = e^{-k^2\sigma_{z2}^2/2}, \tag{5}$$

with $k = \frac{2\pi}{\lambda}$. With our parameters, $B = 0.29$ for the modulator. Note that although $\sigma_{z2} \ll \lambda$, it is a significant fraction of $\lambda$. Nonlinearity in the longitudinal optics will play a role in the microbunch distribution and is yet to be studied more carefully. On the other hand, stray electrons leaking out of the microbuckets due to nonlinearities, quantum excitation and Touschek scattering are still confined by the much larger conventional microwave RF buckets which are maintained during the SSMB operation. The energy modulation by optical laser acts only as a sufficiently deep microbunching potential well to affect the beam's equilibrium Haissingski distribution.

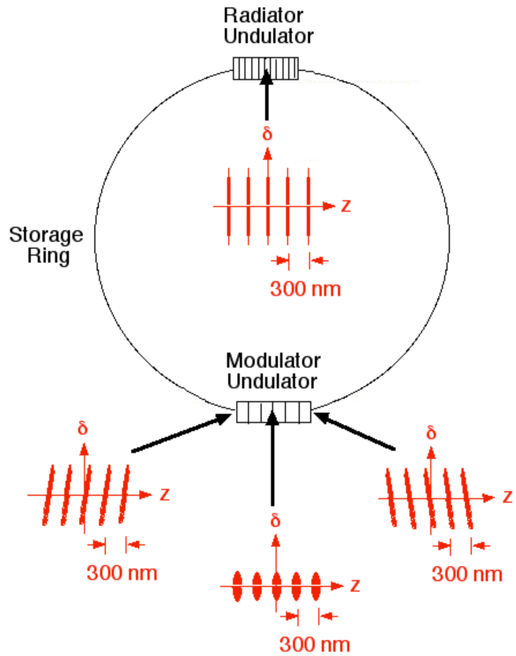


Figure 4: Schematic of longitudinal phase space distribution of the microbunches at various locations around the storage ring.

We now assume that the electron beam in the absence of microbunching has a peak current of $I_p = 17$ A. (The beam has a total length of $L_z = 0.4$ mm containing $N_b = 1.42 \times 10^8$ electrons.) This was the peak current achieved at SPEAR during its low-$\alpha$ runs [12] at 3 GeV, but in order to reach the 1-kW target at the radiator, we here assume the same peak current at 1 GeV. When microbunched, the microbunch peak current reaches 1.04 kA at the radiator. As expected and to be discussed later, the beam suffers from collective effects.

To calculate the radiation power of the microbunched beam in this undulator, we use [14]

$$\hat{P} = \frac{\pi^2 K^2 [JJ]^2}{2(2+K^2)} \frac{N_u N_b^2 B^2 mc^3 r_0}{L_z^2} F_n, \tag{6}$$

where

$$F_n = \frac{2}{\pi}\left[\tan^{-1}\frac{1}{2\xi} + \xi \ln\left(\frac{4\xi^2}{4\xi^2+1}\right)\right], \quad \xi = \frac{2\pi\sigma_\perp^2}{\lambda N_u \lambda_u}, \tag{7}$$

with $r_0$ is the classical radius of electron; $[JJ] = J_0(x) - J_1(x)$ with $J_{0,1}$ the Bessel functions and $x = K^2/(4+2K^2)$; $F_n$ is the diffractive transverse form factor due to the finite transverse size $\sigma_\perp$ of the electron beam. Assuming $I_p = 17$ A and $\sigma_\perp = 120$ $\mu$m, we obtain a peak power of $\hat{P} = 10.9$ kW per

| Storage ring | | |
|---|---|---|
| energy | 1 GeV | |
| $R_{56}$ | 0.5 mm | |
| microbunch synchrotron tune $\nu$ | 0.4893 | |
| electrons per macro-bunch $N_b$ | $1.42 \times 10^8$ | |
| peak electron current before SSMB | 17 A | |
| peak electron current after SSMB | 1.04 kA | |
| Undulator | modulator | radiator |
| resonant wavelength $\lambda$ | 300 nm | 13.5 nm |
| period $\lambda_u$ | 25 cm | 2 cm |
| length $L_u = N_u \lambda_u$ | 2.5 m | 2.5 m |
| strength $K$ | 4.05 | 2.89 |
| integrated modulation voltage $\hat{V}$ | 0.38154 MV | – |
| longitidunal $\beta$-function $\beta_2, \beta_1$ | 7.44 mm | 8.41 $\mu$m |
| beam energy spread $\sigma_{\delta 2}, \sigma_{\delta 1}$ | $1.01 \times 10^{-5}$ | $3 \times 10^{-4}$ |
| beam microbunch length $\sigma_{z2}, \sigma_{z1}$ | 75 nm | 2.52 nm |
| transverse rms beam size $\sigma_\perp$ | 120 $\mu$m | 70 $\mu$m |
| peak radiation power | 10.9 kW | 2.33 MW |
| average radiation power | 4.8 W | 1.04 kW |

Table 1: Parameters chosen as an illustration for an EUV radiation facility.

passage of the bunch through the modulator. This radiation at 300 nm is directed out of the mirror system, either to optical laser users (not optimized for the purpose) or to a dump. The 1-kW target applies only to the EUV radiation, not the radiation at 300 nm.

# 5 Seed Laser Power

Assuming the optical cavity formed by the two mirrors for the optical radiation has a low round-trip loss factor, equivalent to a high quality factor of $Q = 3000$, the needed accumulated seed laser has a peak electric field $\hat{E}_0$ related to its peak power per passage $\hat{P}_{\rm seed}$ by,

$$\hat{E}_0 = \sqrt{\frac{4Q\hat{P}_{\rm seed} Z_0}{R_y \lambda}} \tag{8}$$

where $Z_0 = 376\ \Omega$, $R_y$ is the Rayleigh length. Given $\hat{E}_0$, we use Eq. (2) to calculate the modulation voltage $\hat{V}$. In our SSMB state, we required $\hat{V} = 0.38$ MV. Taking $R_y = 1.5$ m, the required $\hat{P}_{\rm seed}$ is found to be 2.2 kW. Assuming each laser pulse is 0.4 mm long, and a pulse duration of 0.9 m, the required average seed laser power is 0.97 W.

The challenge of the seed laser system is to hold a steady laser strength between the mirrors, with radiated power cleanly extracted. Alternatively, if the seed laser can be 3000 times stronger, it can operate more simply without the mirrors. If feasible, this is a much preferred operation mode because it minimizes any FEL effects in addition to simpler operation.

# 6 Self Generated SSMB

To initiate the SSMB state for the beam, a 300-nm seed laser is used (adiabatically turned on with a running conventional microwave RF). The radiation power levels in Table 1 are results when a seed laser is applied. However, under favorable conditions, the beam should be able to establish the SSMB by itself without the seed laser, although at a reduced radiation power.

Consider an electron beam stored in the storage ring with a conventional microwave RF system. As it passes through the undulator, it initially makes spontaneous radiation at wavelength $\lambda = 300$ nm. With successive passages of electron bunches (not necessarily the same electron bunch), the spontaneous radiation power accumulates between the mirrors. As it accumulates, the coherent wave packets inside the laser pulse increase in their longitudinal length and narrow their spectral width [13]. The radiation wavepacket length is $\sqrt{2\pi}\sigma_{z,rad} \sim N_u\lambda\sqrt{n}$, where $n$ is the number of passages of accumulation. The spectral bandwidth is $\frac{\sqrt{2\pi}\sigma_\omega}{\omega} \sim \frac{1}{N_u\sqrt{n}}$.

The wavepackets continue to grow until they reach diffraction limited saturation when $n_{sat} \sim \frac{L_z}{N_u\lambda}$, where $L_z$ is the length of the electron bunch under conventional RF system without microbunching [13]. Using our parameters, we have $N_u = 10$, $L_z = 0.4$ mm, $\lambda = 300$ nm, the wavepackets saturate in $n_{sat} = 132$ passages. The length of each coherent wavepacket is $\sqrt{N_u\lambda L_z} = 35$ $\mu$m. When no 300-nm seed laser is applied, the electron bunch is microbunched only 9% along its length, and the CW radiation power will be reduced accordingly, although the peak power remains the same.

The peak spontaneous radiation power as a bunch passes through the undulator is calculated to be 4.4 W per passage of a bunch. With 132 accumulations, the saturated power is 580 W. This laser provides a modulation microbunching voltage of 38 kV. Since this radiation saturates quickly, an electron bunch, after it passes through the undulator once, will see a well established radiation seed as it passes through the undulator in its second turn (assuming the number of electron bunches $> n_{sat}$). To see if this established radiation is capable to initiate SSMB mechanism without external seeding, we calculate the bunching factor of the electron bunch in its third turn arriving at the undulator, after it receives $\hat{V}_{2nd} = 38$ kV energy modulation at its second passage. The induced bunching factor at its third passage is $B_{3rd} \approx \pi\frac{e\hat{V}_{2nd}}{E_0}\frac{R_{56}}{\lambda}$. We find $B_{3rd} \approx 0.036$. In order to self-initiate the SSMB process, this bunching factor must be larger than the white noise bunching factor $1/\sqrt{N_b/\sqrt{n_{sat}}} \sim 4\times10^{-4}$ where $N_b/\sqrt{n_{sat}}$ is the number of electrons in the coherent slice in a bunch. This condition is easily fulfilled. The beam will self-SSMB and no external seed is needed for the initiation of the SSMB mechanism.

# 7 A High Power EUV Source

At the position in the arc region exactly opposite to the modulator, the microbunches have a minimum bunch length $\sigma_{z1} = 2.52$ nm. We install the radiator undulator here that resonates at the wavelength of 13.5 nm. See Table 1 for the proposed radiator parameters. The bunching factor is $B = 0.50$. The same assumed bunch as above, but with its rms transverse beam size somewhat focussed down to 70 $\mu$m, is calculated using Eq. (6) to radiate a peak power of 2.33 MW and a CW average power of 1.04 kW.

Assuming the emittances of $\epsilon_x = \epsilon_y = 3.6$ nm at 1 GeV (SPEAR values), a transverse beam size of 70 $\mu$m can be produced with transverse $\beta$-functions of $\beta_x = \beta_y = 1.36$ m at the radiator center. A tighter transverse focusing, not assumed here (we have $F_n = 0.17$), over the length of the radiator can improve the radiation power substantially.

An electron beam also spontaneously radiates by synchrotron radiation as it passes through the two undulators. The radiation losses per electron per passage are 0.26 eV for the modulator and 67 eV in the radiator. The undulators and the seed lasers are chosen sufficiently weak so their perturbations to affect the SSMB mechanism is minimized. In particular, it is envisioned that the beam passes through the two undulators every turn, and not separated out after each passage for it to radiation damp.

However, as mentioned, collective effects must be evaluated for the 1-kW power target. The small energy spread ($\sigma_\delta = 3 \times 10^{-4}$ at the radiator) and the high peak current (1.04 kA at the radiator when the beam is microbunched) assumed in this scenario puts the beam at the risk of intrabeam diffusion and coherent synchrotron radiation (CSR) instability. The energy spread diffusion time of the microbunched beam due to intrabeam scattering is estimated, assuming a fully coupled beam, to be about 124 ms, which is longer than the synchrotron radiation damping time 53 ms. The maximum growth of CSR instability is estimated to occur at wavelengths much longer than the microbunch length. However, the energy distortion due to the CSR wake in the radiator is much larger than the beam energy spread and threatens to destroy the microbunching buckets. More careful studies are needed to evaluate these effects.

One way to mitigate the intrabeam diffusion and CSR instability problems is to return to staggered buckets, which so far has not been implemented in our example. If the storage ring has an energy aperture $A_\delta = 1.2\%$, we can stagger up to $h = 40$ microbunch strings. Beam intensity per microbunch can in principle be reduced substantially if the radiator is properly located in the storage ring.

Another potential issue is due to SASE effect in the two undulators at average peak current (before microbunching) of $I_p = 17$ A. FEL gain lengths are 5.7 m in the modulator and 2.1 m in the radiator. For the microbunched beam, coherent shifting can be tolerated, but smearing in $\delta$ or $z$ can be a potential issue. Simulations are needed to address this.

While the SSMB mechanism is expected to be feasible in an existing SPEAR-like storage ring at low beam currents, whether a 1-kW EUV power is feasible will depend on more study results, and possibly also on the feasibility of a staggered operation mode.

## 8 Double modulator

In case the storage ring can only tolerate a larger $R_{56}$, or in case $\nu$ must not be too close to 0.5 causing a large longitudinal $\beta$-beat, one way to proceed is to split the modulator into two (1.25 m each), and move them closer to the radiator symmetrically. The space opened up between them can accommodate a larger $R_{56}$ and reduce the $\beta$-beat. This scenario, if needed, has to be studied in detail by a design re-optimization.

## 9 Test proposal

SPEAR low-$\alpha$ operation [12] has reached $R_{56} = 13.8$ mm. In this operation at 3 GeV, a single bunch contained $1.74 \times 10^9$ electrons with an rms bunch length of 1.9 mm (peak current 17.5 A), and $R_{56}$ could be lowered to 0.92 mm as the beam intensity is lowered. We have assumed a value of $R_{56} = 0.5$ mm. Assuming this is achievable (or otherwise using a double modulator scheme mentioned in Section 8), SPEAR can be a candidate for testing the proposed SSMB mechanism. The bunch length $\sqrt{2\pi}\sigma_z = 0.4$ mm and energy spread $\sigma_\delta = 0.024$ % can be achieved if SPEAR is operated at an RF voltage of 140 kV.

An unperturbed peak current of 17 A before turning on the laser modulation, assumed in the present design in order to reach 1 kW power target, requires the number of electrons per bunch of $1.42 \times 10^8$. The total number of bunches is 280. Average beam current is 6 mA. While this is quite feasible, it is expected that the CSR may forbid the formation of microbunches at this beam current when the seed laser is turned on, unless the beam is operated with staggered buckets.

## 10 Dedicated Storage Ring

As mentioned, SPEAR or an existing SPEAR-like ring would be ideal for testing the SSMB mechanism. To approach 1 kW, however, it will require a further demonstration of staggered buckets. Alternatively, a dedicated ring may be considered to provide much needed flexibility to lower the peak current of the electron beam, or eventually to raise the radiation power beyond the target of 1 kW. Examples of the parameters to vary that will help to raise the radiation power are, among other possibilities:

- The momentum compact factor is a sensitive parameter. A value $R_{56} <$ 0.5 mm can substantially relax the collective effects and the longitudinal lattice design.

- A shorter wavelength for the conventional microwave RF (e.g. by using C-band or X-band) allows more bunches in the storage ring, thus lowering the peak current.
- Longer bunches before microbunching allows more microbunches within each bunch, thus lowering the microbunch peak current.
- Transverse beam emittances can be sensitive parameters to vary for optimization.

More detailed work is needed if a dedicated ring is to be considered.

# 11 Summary

The storage ring SSMB mechanism is applied to aim for a 1-kW CW EUV radiation source at 13.5 nm wavelength appropriate for lithography applications. The suggested parameters in this attempt assimilate SPEAR low-momentum-compaction operation mode but at a momentum compaction comparable or lower than what it has ever reached. Staggered buckets are needed to mitigate collective effects at the high required peak beam currents needed to reach 1 kW if a SPEAR-like ring is used. A much more flexible alternative is to consider a new dedicated ring to reach the same goal.

Several technical issues will require more detailed studies:

- Can the storage ring operate at the required low momentum compaction and high peak current?
- Does coherent synchrotron radiation destroy the microbunch buckets without staggering?
- Can the storage ring operate with staggered buckets?
- Does SASE diffuse the microbunches?
- In case of considering a dedicated ring for 1 kW, a detailed optimized design is needed.

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