HIGH POWER RADIATION SOURCES USING THE STEADY-STATE MICROBUNCHING MECHANISM

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Abstract

The mechanism of steady-state microbunching (SSMB) was proposed for providing high power coherent radiation using electron storage rings. The mechanism follows closely the RF bunching in conventional storage rings, with the RF system at a microwave wavelength replaced by a seeded laser in an undulator at an optical wavelength. No FEL mechanism, and thus no FEL energy heating, is invoked. The basic idea is firstly to make the beam microbunched so that its radiation becomes coherent, and secondly to make the microbunching a steady state so that the coherent radiation is maintained at every turn. The combination of the high repetition rate of a storage ring and the enhanced radiation power by a factor of $N_{\rm coh}$ (the number of electrons in the microbunches within one coherence length) opens the possibility as well as challenges of very high power SSMB sources. To explore its potential reach, we apply SSMB to the infrared, deep ultraviolet and EUV regions and estimate their respective power levels. Several variants of the SSMB schemes are discussed. A proof-of-principle configuration without an identified testbed is also suggested.

MOTIVATION AND SSMB

Among the many applications for high-power coherent radiation sources, some do not demand high brilliance or high peak power. Instead, they focus on having an extremely high average-power not available in some of the peak-power devices. High average-power coherent sources have applications in many areas, from research tools to industrial applications. One example is an EUV source capable of kilowatt power per tool for lithography. With this motivation, I will introduce a high-average-power scheme, called the Steady-State Microbunching (SSMB). SSMB is still at an early R&D stage. I will give a progress report, and describe what SSMB is — and also what it is not.

The technology of accelerator-based coherent radiation sources has been driven by two user demands: shorter wavelength and higher power. For example, they drove the invention of the free electron laser for a powerful source up to the Xrays. In an FEL, the high power comes from the electron beam microbunching, while the short wavelength comes from the short length of these microbunches.

Microbunching is a wonderful thing. The microbunched electron beam in an FEL not only allows the radiation frequency to be raised to Xrays, but also due to the coherence of the radiation process, the power of radiation is increased by a factor of $N_{\rm coh}$, where $N_{\rm coh}$, the number of electrons in the microbunches within one coherence length, is a large number. The peak power of the FEL radiation is therefore extremely high due to the microbunching factor of $N_{\rm coh}$.

	f[GHz]	bunch length	microbunch length	$N_{\rm bunch}$	$N_{\rm coh}$
Conv.stor.ring	0.3	1 mm		10^{11}	1
Supcond.FEL	1	1 mm	$< 1\ \mu$m	10^9	10^7
SSMB	3×10^5		$< 1\ \mu$m	10^5	10^5

Table 1: Comparison of SSMB with conventional storage ring and FEL.

However, although its peak power is extremely high, FELs average power is typically low because FELs use linacs, and linacs have notoriously low repetition rates.

The issue of repetition rate brings to the consideration of storage rings. The traditional synchrotron radiation sources produce high power because of the high repetition rates. Without the enhancement of microbunching, however, their peak-power is low.

It seems apparent that to make a next step in the development of high power coherent radiation sources, one must try to keep the high peak power due to coherence, while somehow maintain a high repetition rate. Repetition rate is readily available from storage rings. The high peak power requests the beam to be microbunched. This leads to our subject of a "steady state microbunching" (SSMB) scheme [1].

The low repetition rate of FELs can be relieved by invoking superconducting linac and energy recovery technologies, raising from 120 Hz to ~1 GHz. In contrast, the SSMB aims for CW stream of microbunches spaced by optical distances. The GHz FEL has peak power several orders higher than the SSMB, while SSMB optimizes the repetition rate. One can also compare SSMB with the conventional storage rings. SSMB manipulates the storage ring beam dynamics so that the electron beam becomes microbunched with microbunch length $\ll$ intended radiation wavelength λ, and with short phase-locked spacing. All electrons in each microbunch and its neighboring microbunches radiate coherently.

Three quantities enter the average radiation power P_r: the repetition rate f, the number of electrons per bunch $N_{\rm bunch}$, and $N_{\rm coh}$. Other than geometric factors, P_r scales with $f N_{\rm bunch} N_{\rm coh}$. See Table 1.

The SSMB microbunching mechanism is the same as that of beam bunching in a conventional microwave RF system. The RF system bunches the beam with a bunch spacing equal to the microwave wavelength, and the bunching is established as a steady state on a turn-by-turn basis. Also, the RF system provides a longitudinal focusing so that the electron bunch has a length $\ll$ the RF wavelength. A similar approach is taken for the SSMB. The modulator system consisting of an infrared seed laser of wavelength λ_m and a co-propagating

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undulator resonant with λ_m replaces the RF system. The final beam is microbunched with microbunch spacing equal to λ_m. Depending on the applications, the modulator could provide extra longitudinal focusing so that the equilibrium microbunch length $\sigma_z \ll \lambda_m$.

When $\sigma_z \ll \lambda_m$, coherent radiation can be extracted from the microbunches at a higher harmonics of the seed laser, $\lambda = \lambda_m/h$ as long as $\sigma_z \lesssim \lambda/2\pi$. With h an integer, not only each microbunch, but also all microbunches within one coherent length, radiate coherently. For an application to lithography EUV radiation, for example, SSMB aims for h ~10-20, and extra longitudinal focusing, i.e. "strong focusing" is required.

On the other hand, the extra longitudinal focusing is applied only as needed. When not applied, i.e. in the "weak focusing" cases, the resulting beam is only potential-well distorted to form a microbunch modulated distribution, and has a relatively small bunching factor. Harmonic generation h is then limited to 1 or low values.

Depending on the applications, the seed laser may or may not be stored in a laser cavity consisting of mirrors. For proof-of-principle test of microbunching mechanism or for weak focusing SSMB without harmonic generation ($h = 1$), a single pass seed laser without mirrors suffices. For high power applications, however, mirrors are needed to boost the laser voltage at the modulator.

It is important to note that the SSMB does not invoke an FEL mechanism. The microbunching is established as an equilibrium steady state. The beam enters the modulator premicrobunched at each revolution. The undulator length is a small fraction of the FEL gain length. There is no energy heating and no laser gain at each passage as in a SASE FEL. The approach of storage ring FEL [2], as well as its limitation due to energy heating [3], does not apply here. These approaches offer higher peak power but the electron beam is disrupted after each passage and needs radiation damping to recover. These are not steady-state approaches; the high repetition rate of a storage ring is not utilized.

There will be some degree of unavoidable SASE occurring at each passage. With the radiation per passage several orders of magnitude weaker than a typical SASE FEL, this effect is expected to be weak, and when occurring, it is to be controlled similarly to how beam loading is controlled in the conventional RF systems. A Robinson-type instability will have to be dealt with. Feedback systems are required to maintain the net energy modulation, both in phase and amplitude, in the beam-loaded seed laser system.

Each SSMB insertion contains two modulators sandwiching one radiator. See Fig.1. The microbunched beam goes through the radiator to radiate coherently at the desired wavelength λ. The radiator is a passive device. Its radiation is sent to users without accumulation. The setup is sketched below. Each modulator provides modulation voltage of $V_m \sin(2\pi z/\lambda_m)$. Between each modulator and the radiator is a dispersion section with momentum compaction R_{56}, introduced to harmonic generate $h \gg 1$.

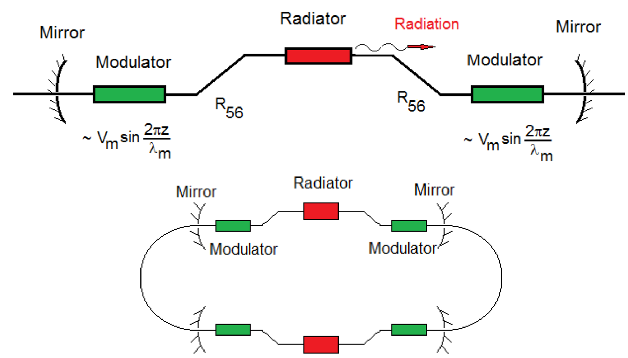

Figure 1: An SSMB insertion and a storage ring with two SSMB insertions.

The required hardwares for SSMB depends on the applications. Including a strong focusing for harmonic generation, the required hardware is demanding but should be reachable.

Storage ring The ring energy is chosen $\gtrsim$ a few 100 MeV's to minimize collective effects. To control the intrabeam diffusion, and not considering high brilliance, the ring does not have a low-emittance lattice. The most demanding requirement is for a small R_{56} per SSMB tool. The momentum compaction factor is $\alpha_C = nR_{56}/C + 1/\gamma^2$, where n is the number of SSMB tools in the ring, C is the ring circumference. If α_C is limited in its lower reach, small C and large n will be preferred. Relieving the lattice from low emittance should help achieving small α_C (easier dynamic aperture) although higher order momentum compaction needs to be controlled by sextupoles. Small α_C was also suggested before for a storage ring FEL operation [4].

Two modulators Each modulator consists of an undulator (~2 m, 2 T) and a co-propagating seed laser. With a modest beam energy, the undulator needs to have a relatively large strength K_m resonant with the seed laser wavelength λ_m.

Radiator An undulator (~1-2 m, 1-2 T) is to be installed between the two modulators.

Seed laser and mirrors The infrared seed laser is stored in a cavity consisting of two high reflectivity mirrors. We assume that the system is limited by the maximum stored laser power in the laser cavity at 1 MW. With 1 MW stored power, the required seed laser average power is 1 kW if the mirror cavity has a reflectivity $r_f = 0.999$. The advertised radiation power scale linearly if the limit of the stored laser power has a different value. Synchronization of the seed laser phase relative the arriving electron bunches at both of the modulators is to be assured to an accuracy $< \lambda_m/2\pi$.

Induction linac The power source for average beam acceleration is considered a solid state induction linac of length ~ 1 m, repetition rate up to ~a few MHz, and pulse voltage ~10 kV. The induction pulse covers part of a revolution every revolution time sufficient to cover the filled beam. Depending on the pulse structure of the induction linacs, multiple units can be used as needed to reduce the pulse repetition rate for each unit. Induction linac is not needed in a proof-of-principle test.

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SSMB SCENARIOS

There are several SSMB scenarios proposed in the past [1,5,6]. Eventually, a challenge will be to identify the optimal scenario for each desired radiation wavelength. Our present main effort, the "strong focusing SSMB", emphasizes the need of a high harmonic generation, and is the more challenging among the scenarios.

1. Reversible SSMB This is the conceptually simplest SSMB scheme [6]. In this scheme, the nominal SSMB insertion is modified so that the downstream section now contains a dispersion section $-R_{56}$ and a modulator with $-V_m \sin(2\pi z/\lambda_m)$, i.e. the reverse of the upstream section. The upstream section functions similarly to an HGHG section in an FEL. The downstream section then removes the HGHG effects so that there is no net effect in the rest of the storage ring. Between these two insertions, the beam is microbunched, providing coherent radiation at the radiator. The beam is not microbunched outside of the insertion.

The bunching factor at the radiator for harmonic h is

$$b_h = e^{-2\pi^2 h^2 R_{56}^2 \sigma_\delta^2/\lambda_m^2} J_h(-\frac{2\pi h e V_m R_{56} \sigma_\delta}{\lambda_m E_0 \sigma_\delta})$$

where σ_δ is the rms relative energy spread of the beam entering the upstream modulator, E_0 is the beam energy.

This SSMB scenario has the advantage that it minimizes the impact on the storage ring operation including α_C. However, it is a significant lattice design complication to produce an opposite sign $-R_{56}$. Also, the required energy modulation is large and the reachable maximum harmonic h is limited. Although useful if no harmonic generation is required, we have not focused on this scenario.

This reversible scenario can be extended by replacing the HGHG section by an EEHG section (and reversed EEHG downstream) to reduce the required modulation voltage and/or to enhance the harmonic generation. Still another variation along this line, based on a PEHG scheme [7], has also been proposed. With sufficiently weak energy modulation, a reverse PEHG might not be required.

2. Staggered microbucket SSMB This is chronologically the first SSMB concept proposed [1]. As mentioned, the SSMB mechanism generates a microbucket string at a microbucket spacing of λ_m. When λ_m is short enough $\sim\mu$m, the momentum acceptance of the storage ring can accommodate multiple bucket strings staggered in momentum space. In addition to the nominal string, additional strings above and below it are now possible in which each bucket shifts by an integral multiple of λ_m per revolution of the beam. The number of staggered bucket strings is $h = 2A_\delta R_{56}/\lambda_m$. where $\pm A_\delta$ is the momentum aperture of the storage ring. For example, h can be large $\sim$ 10.

By locating a radiator a certain distance downstream from the laser modulator, the h strings slip in their relative longitudinal positions so that the beam now splits into h microbuckets interlaced evenly by a distance λ_m/h and a harmonic generation of a factor h is reached. The case $h = 3$ is shown

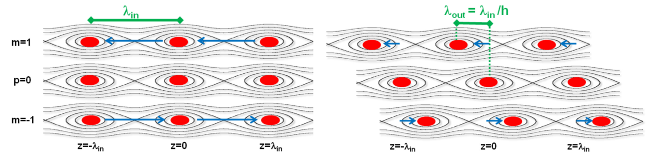

Figure 2: Staggered microbucket SSMB scenario with $h = 3$.

in Fig.2, viewed at the modulation point (left), and viewed 1/3 around the ring (right).

A further increase of harmonic generation was also considered using the bifurcation of the microbunch buckets [5].

Staggered bucket scenario has the complication that the migration of the microbuckets requires controlling and manipulating the longitudinal phase space over long distances. One way to do so is to implement a barrier RF buckets, so that that entire microbunch train stays within the RF barriers.

3. Frequency beating THz SSMB A variation occurs when the infrared laser modulator is replaced by two modulations of nearly equal wavelength, $\lambda_1 = \frac{b}{b-1}\lambda_2$, so that the beam is microbunched at the beat wavelength $\lambda_m = \frac{\lambda_2}{b-1}$ [1]. The steady state beam will have SSMB spacing equal to the beat wavelength. This is a way to produce coherent THz radiation. Only one undulator is needed for the modulations if $\lambda_{1,2}$ are both within the undulator bandwidth.

4. Strong focusing SSMB To push up the harmonic generation factor $h \gg 1$, the modulators sandwiching the radiator have an additional task of strongly focusing the bunch not unlike the interaction region quadrupoles in a collider. With the requirement to produce a small bunch length at the radiator located at the focal point, Courant-Snyder analysis is invoked with longitudinal β-function. The energy spread and length of the microbunches vary around the ring. Stability of the microbunches requires

$$|\cos \pi \nu_s| = \sqrt{\left(1 + \frac{2\pi e V_m R_{56}}{E_0 \lambda_m}\right)\left(1 + \frac{2\pi e V_m R'_{56}}{E_0 \lambda_m}\right)} < 1$$

with R_{56} and R'_{56} the momentum compactions from the radiator to the modulator and from the modulator to the superperiod symmetry point, and ν_s the resulting synchrotron tune. Fulfilling this condition avoids re-randomization after each radiation passage. It roughly requires $|2\pi e V_m R'_{56}/E_0| \lesssim \lambda_m$. There is a trade-off between V_m and R'_{56}.

With intentional strong focusing, the longitudinal phase space evolution of one microbunch over one superperiod is sketched in Fig.3 showing harmonic generation. The beam distribution repeats turn-by-turn in steady state.

5. Amplifier SSMB Depending on applications, a relaxed and simple version of SSMB content with $h = 1$ can let go of the strong focusing. This scenario becomes a pure extension of conventional storage rings replacing the bunches by microbunches. The SSMB serves effectively as an amplifier of the seed laser, with a more substantial radiator and an induction linac serving as a pumping energy source. With an EUV seed laser source installed, for example, the scenario can

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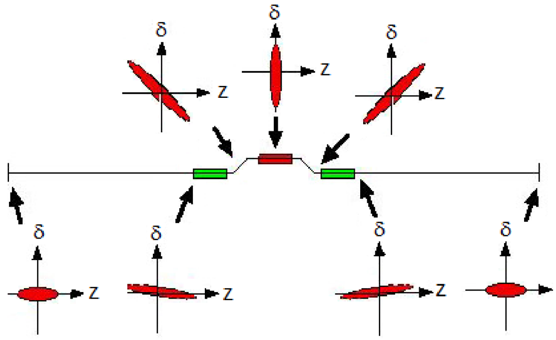

Figure 3: Microbunch phase space for one SSMB superperiod.

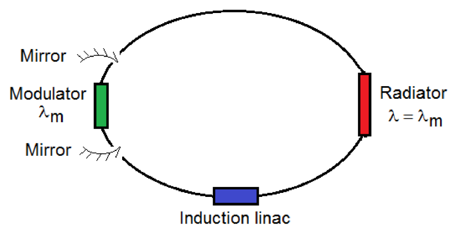

Figure 4: An amplifier SSMB.

be used to amplify its EUV power. The microbunch length is constant around the ring including at the radiator. The microbunching modulation can be shallow with an overall confining buckets. See Fig.4.

NUMERICAL EXAMPLES

SSMB can be scaled to a range of frequencies. Table 2 lists three cases (IR, DUV, EUV) for the strong focusing SSMB scenario. The advertised radiation power are in the >kW range. The parameters optimization is rather broad. The list is only example cases. We assume two tools in these examples ($n = 2$). Filling factors refer to the percentage the microbunched beam filling the circumference. It is determined by imposing the condition that the stored power of the seed laser in the mirror cavity reaches 1 MW. With a mirror reflectivity $r_f = 0.999$, the seed laser average power is 1 kW per tool in all cases. The heating power to be removed is 1 kW per tool.

One critical requirement is on the small α_C, especially for the EUV case. The radiation power P_r depends on α_C/n sensitively. If the required value is not reached, the radiation power drops quickly. Similarly, if α_C can be made smaller, the gain in P_r is drastic. Other issues are discussed below.

Coherent synchrotron radiation The 1-D CSR stability threshold for peak current is [8]

$$\hat{I}_{\rm th} = \sqrt{\frac{1}{2\pi}}\, I_A \gamma \left(1 + 0.68\,\frac{\rho^{1/2}\sigma_{zm}}{g^{3/2}}\right) \sigma_{\delta m}^2 \frac{|R_{56}^{(b)}|}{(\rho\sigma_{zm}^2)^{1/3}}$$

where $I_A = 17$ kA, g is the full gap size of shielding vacuum chamber. For all cases, we choose $\hat{I} = \hat{I}_{\rm th}$, i.e the CSR determines the peak current. The 2-D suppression of the CSR effect when $\sigma_\perp \gg (\sigma_z^2\rho)^{1/3}$ is not taken into account.

		IR	DUV	EUV	
E_0	beam energy	400	400	400	MeV
C	ring circumference	50	50	50	m
α_C	mom. comp. factor	18.4	8.8	0.27	10^{-6}
$\hat{V}_m$	modulator voltage	−0.42	−0.75	−0.51	MV
N_μ	electrons/microbunch	14.6	2.2	0.04	10^5
I_0	ave. beam current	2.05	0.41	1.02	A
$\Delta\delta_{\rm CSR}$	CSR pot. well distort.	2.5	2.3	2.4	10^{-3}
$\tau_{\rm RW}$	resist.wall growth time	0.28	1.4	0.67	ms
$\tau_{\delta,\rm IBS}$	IBS diffusion time	48	51	80	ms
L_m	modulator length	2.1	2.0	2.0	m
K_m	modulator strength	18	12	4.2	
λ_{um}	mod.undulator period	9.6	6.5	2.2	cm
λ_m	seed laser wavelength	12.9	4.0	0.176	μm
$P_{\rm stored}$	laser stored power	1	1	1	MW
$P_{\rm seed}$	ave. seed laser power	1	1	1	kW
h	harmonic number	11	17	13	
L_r	radiator length	0.86	2.0	2.5	m
K_r	radiator strength	8	4.6	1.2	
λ_{ur}	rad. undulator period	4.3	2.5	1.0	cm
λ_r	SSMB rad.wavelength	1.18	0.24	0.0137	μm
F	filling factor	38%	16%	93%	
P_r	SSMB rad.power/tool	4.2	1.4	1.12	kW

Table 2: Three strong focusing SSMBs for IR, DUV, EUV.

In addition to instability, the CSR also induces a distortion in microbunching potential well by

$$\Delta\delta_{\rm CSR} = \pm 0.4\sqrt{\frac{\pi}{2}}\frac{4\pi\hat{I}}{\gamma I_A}\left(\frac{\rho}{\sigma_z}\right)^{1/3}$$

This CSR distortion does not disrupt the microbunching mechanism as much as the instability does; 2-D suppression should also help.

Resistive wall instability Single bunch instabilities are not serious with low single-bunch intensities, but the average beam current is high, so coupled bunch instabilities are a concern. The resistive wall instability growth rate is

$$\tau_{\rm RW}^{-1} = \frac{8r_e c(I_0/e)}{\gamma\sqrt{2\pi\sigma_c\omega_0|\Delta_\beta|}}\langle\frac{\beta_y}{g^3}\rangle$$

with β_y the vertical β-function, σ_c the wall conductivity, and ω_0 the revolution frequency. Assuming the same vacuum chambers as SPEAR3 in all cases, τ_{RW} are found to be short. The resistive wall instability, however, is a narrow-band effect. Together with the low beam energy, the required feedback power is in the watt range.

Intrabeam scattering The IBS energy diffusion rate is [9]

$$\tau_{\delta,\rm IBS}^{-1} \approx \frac{0.688\,N_\mu r_e^2 c L_C}{8\gamma^3\sigma_{zm}\sigma_{\delta m}^2\langle\sigma_x\rangle\epsilon_{\perp 0}}$$

where the Coulomb log $L_C = 12$. In the three cases, $\tau_{\delta,\rm IBS}$ are kept to be > 3 × the radiation damping times.

Seed laser The modulation voltage V_m is related to the peak electric field $\hat{\mathcal{E}}_0$ of the seed laser by $eV_m = \frac{e\hat{\mathcal{E}}_0 K_m}{2\gamma} L_m$. The peak power of the stored accumulated laser is

$$\hat{P}_{\rm seed} = \frac{(e\hat{\mathcal{E}}_0)^2 R_y \lambda_m}{16\pi m_e c r_e}$$

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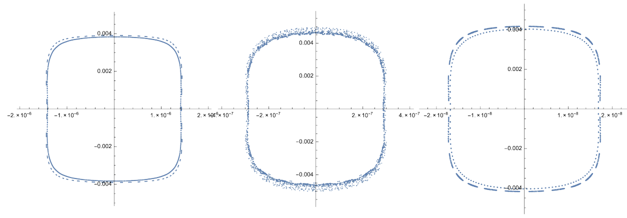

Figure 5: Tracking stability of the three SSMBs.

where R_y is the Rayleigh length. The seed laser provides a power for $P_{\text{seed}} = (1 - r_f)\hat{P}_{\text{seed}}$. We assume the limit of the mirrors is set by a maximum stored laser power at 1 MW.

The seed laser system requires a state-of-the-art technology. Its strength is to be held steady between the mirrors by precision feedback systems. Phase jitter turn-by-turn is to be controlled to $< \lambda_m/2\pi$. (Note it is not $< \lambda/2\pi$ as in most coherent sources.) Tolerance on the laser pulse envelope however is much more relaxed.

The laser system has a range of possibilities for optimization. Other than the case being considered, if needed, one approach to reduce the seed laser power is to divide the modulators into smaller pieces with reduced Rayleigh length. Another approach is to consider an over-moded waveguide to confine the laser. Applying a dielectric laser acceleration is another possibility. One more intriguing approach is to self-seed the modulators, sparing the seed laser altogether. On the other hand, if high power seed laser is available, one can consider yet another option of single shot seeding without mirrors.

Stability of the microbunch buckets The three cases are tracked for 1000 turns in the synchrotron phase space with the linearized voltages replaced by proper sinusoidal wave forms. See Fig.5. To minimize the modulation nonlinearities, λ_m is taken to be ~20 times the microbunch length σ_z. We require all cases to have at least a 6σ stability region, maintaining sufficient quantum lifetimes.

Radiator The radiator is a passive device. Its power in the fundamental mode at wavelength λ_r is [10]

$$P_{\text{rad}} = 2\pi^2 r_0 m_e c^3 F|B|^2 \frac{K_r^2}{2 + K_r^2}[JJ]^2 \frac{N_u N_\mu^2}{\lambda_m^2}$$

where B = bunching factor, N_u = number of undulator periods, $[JJ] = J_0(\chi) - J_1(\chi)$, $\chi = K_r^2/2/(2 + K_r^2)$, $F = \frac{2}{\pi}\left[\tan^{-1}(\frac{1}{2S}) + S\ln(\frac{4S^2}{4S^2+1})\right]$, $S = \frac{2\pi\sigma_{\perp r}^2}{\lambda_r L_r}$ with transverse electron radius $\sigma_{\perp r}$ and radiator length L_r.

PROOF-OF-PRINCIPLE TEST PROPOSAL

Feasibility of SSMB has not been established experimentally. We suggest that a proof-of-principle test is required and can proceed with a minimum test with a single RF bucket bunch (quiet superconducting RF is preferred) in an existing ring, perhaps of 3 GeV but run at a lower energy and low α_C. (SPEAR3 had reached $\alpha_C = 3 \times 10^{-6}$ at 3 GeV [11].) We propose to test a weak focusing SSMB using a single-pass laser (1 μm, 100 μJ, 1.5 MHz, no mirrors), and the beam is shallow microbunched at the laser wavelength without harmonic generation. See Table 3.

Electron energy	500 MeV
Modulation wavelength (λ_m)	1 μm
Mom. comp. factor (α_C)	2 10^{-6}
Und. strength K	6
Undulator period, # periods	10 cm , 10
Beam current	0.5 μA
Laser phase jitter (turn-by-turn)	0.2 fs
Laser waist (rms), pulse length	2 mm, 1 ps
Laser average power	4 W

Table 3: Proof of principle test.

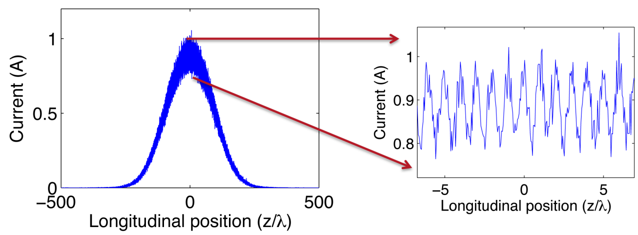

Figure 6: Simulation of microbunching in the proof of principle test.

Simulation of the shallow microbunching is shown in Fig.6. This bunching factor (~ 5%) is detectable even at the low beam current by simply switching off the seed laser. The turn-by-turn jitter tolerance is smaller than measurement capability. However, what is important is the jitters approaching the synchrotron oscillation frequency. Preliminary simulations indicate the phase jitter tolerance of 60° when the jitter frequency is 300 turns.

CONCLUSION

We considered the challenge to make use of a microbunched beam in steady-state in storage rings, with the attempt to make use of the last frontier of major improvement, i.e. the factor of N_{coh} in the storage ring radiation power. Several SSMB scenarios have been proposed. Parameter optimization of an SSMB tends to be rather broad. The choice of appropriate scenario and optimized design depends on application. For applications that require both high average power and short wavelength, the scenario we paid most effort is a strong focusing scenario. Three non-optimized examples were presented, for IR, DUV and EUV wavelengths, each with > 1 kW power per tool.

More dedicated in-depth design and optimization work remains to be done, including a proof-of-principle test on an existing storage ring. Other technical issues include the low-α_C operation, state-of-the-art solid state induction linac, the seed laser feedback system together with the jitter tolerances. But the basic idea looks sound, and if accomplished, the rewards are high.

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