High Power Radiation Sources using the Steady-state Microbunching Mechanism

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- Not all radiation sources demand high peak power. Some demand high average power.
- Example: kilowatt EUV source for lithography.
- With this motivation, I will introduce a high-average-power scheme, called the Steady-State Microbunching (SSMB).

[Ratner, Chao (2010)]

- The technology of coherent radiation sources has been driven by two demands: shorter wavelength and higher power.
- In an FEL, the high power comes from the electron beam <u>microbunching</u>. The short wavelength comes from these microbunches are very short.

Two requirements for high average power:

1. Microbunching

The beam must be microbunched. The peak power x N_{coh}, the number of electrons in the microbunches within one coherence length. $N_{coh} \sim 10^{5-7}$ in SSMB.

2. Steady state

This brings to the consideration of storage rings. The microbunched beam must be in steady state, i.e. it maintains the microbunched state on a turn-by-turn basis.

This combination leads to ``steady state microbunching''.

Compare SSMB with conventional storage rings and FELs:

	f[GHz]	bunch length	microbunch length	N_{bunch}	N_{coh}	$fN_{\mathrm{bunch}}N_{\mathrm{coh}}$
Conv. storage ring	0.3	1 mm		10^{11}	1	0.3×10^{11}
Supcond. FEL	1	1 mm	$< 1\ \mu$m	10^{9}	10^{7}	10^{16}
SSMB	3×10^{5}		$< 1\ \mu$m	10^{5}	10^{5}	3×10^{15}

- The average radiation power ~ $fN_{bunch}N_{coh}$.
- Conventional storage rings are not microbunched. SSMB aims to microbunch with phase-locked infrared spacing, microbunch length < λ.
- FEL repetition rate can be increased by superconducting linac and energy recovery technologies to ~1 GHz. SSMB aims for CW stream of microbunches with repetition rate ~$3\text{x}10^5$ GHz.

- The SSMB microbunching mechanism is the same as a conventional storage ring except that the microwave RF system is replaced by a modulator system consisting of an infrared seed laser of wavelength λ_m and an undulator.

  Conventional ➔ bunch spacing = RF wavelength

  bunching is a steady state

  electron bunch length << the RF wavelength.

  SSMB ➔ microbunch spacing = λ_m

  extra focusing can yield microbunch length $\sigma_z \ll \lambda_m$

- When $\sigma_z \ll \lambda_m$, coherent radiation at a higher harmonics

  $$\lambda = \lambda_m/h \quad (h = \text{integer})$$

  ➔ All microbunches within one coherent length radiate coherently.

  For lithography EUV radiation, SSMB aims for h = 10-20, and ``strong focusing'' harmonic generation is required.

- On the other hand, one can also have a ``weak focusing'' case, the resulting beam is only microbunched by potential-well modulation

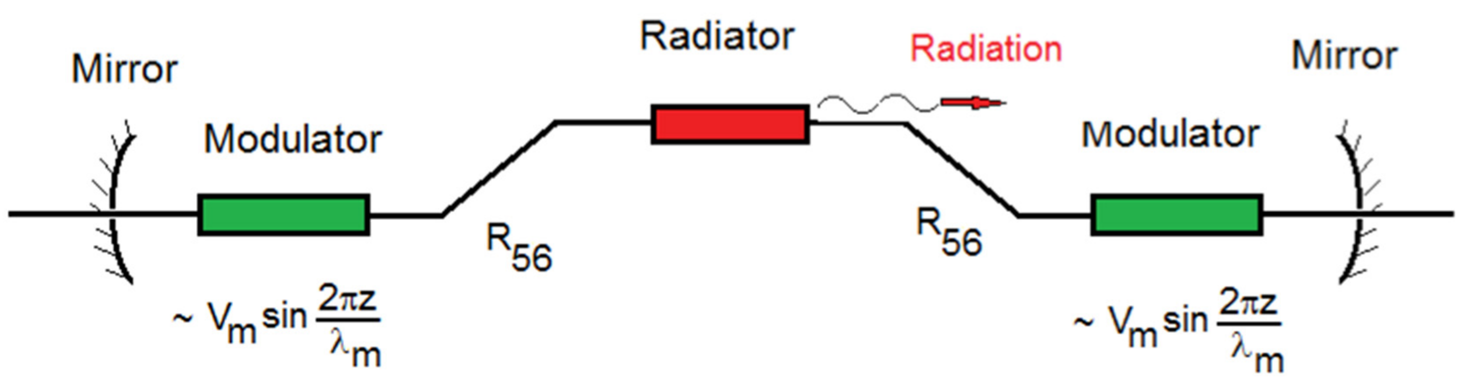
  ➔ Relatively small bunching factor and h = 1, or a few.

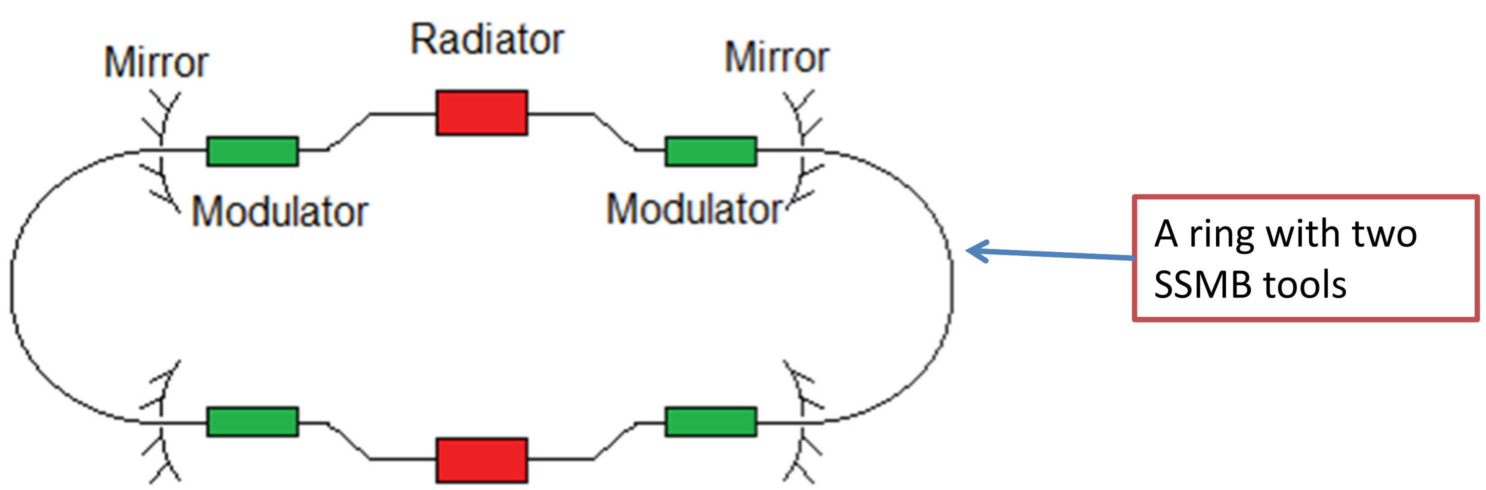
It is important to note that the SSMB does not invoke an FEL mechanism. SSMB is not a storage ring FEL.

[Elleaume (1985); Billardon et al. (1983); Couprie (1996); Rinieri (1977); Deacon, J. Madey (1980)]

The electron beam is not disrupted after each passage and does not need radiation damping to recover, thus allowing a turn-by-turn operation.

- Each SSMB insertion = two modulators sandwiching one radiator.
- The microbunched beam goes through the radiator to radiate coherently at λ.
- The radiator is a passive device. Its radiation is sent to users without accumulation. Mirrors are for the seed laser only.





SSMB scenarios

There are several SSMB scenarios proposed. Optimal scenario depends on the desired radiation wavelength. Our present main effort is the ``strong focusing SSMB'', emphasizing the more challenging cases with h >> 1.

1. Reversible SSMB

- The downstream section of the modulator is replaced:

  $R_{56} \rightarrow - R_{56}$, $V_m \sin(2\pi z/\lambda_m) \rightarrow - V_m \sin(2\pi z/\lambda_m)$
- The upstream section functions similarly to an HGHG section in an FEL. The downstream section removes the HGHG effects.

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

- This is the simplest SSMB. The beam is not microbunched outside of the insertion.
- This scenario minimizes the impact on the storage ring operation.
- However the required energy modulation is large and the maximum h is limited.

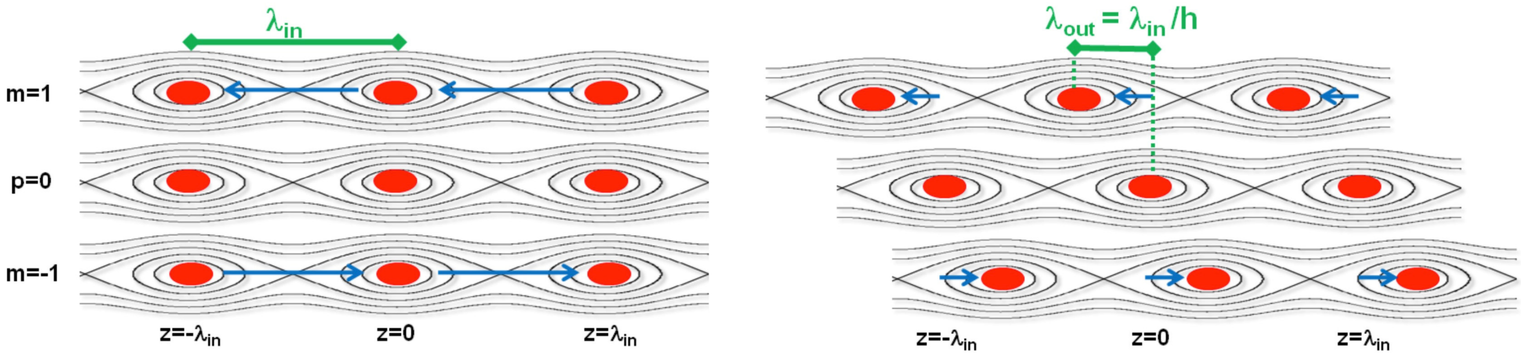
2. Staggered microbucket SSMB

- When λ_m ~ 1 μm, the storage ring can accommodate multiple bucket strings staggered in momentum space. Additional strings appear in which each bucket shifts by an integral multiple of λ_m per revolution. The number of staggered bucket strings is

$$h = 2 A_\delta R_{56} / \lambda_m$$

where $\pm A_\delta$ is the momentum aperture of the storage ring. For example, h ~10.

- By locating a radiator a certain distance downstream from the modulator, the beam splits into h microbuckets. Harmonic generation of a factor h is reached.



- Staggered bucket scenario requires controlling the longitudinal phase space over long distances. A barrier RF bucket might be required.

3. Frequency beating THz SSMB

An SSMB variation occurs when the infrared seed laser is replaced by two lasers of nearly equal frequencies f_1 and f_2.

The beam is SSMB microbunched at the beat frequency $f_1 - f_2$. This SSMB radiates at e.g. THz.

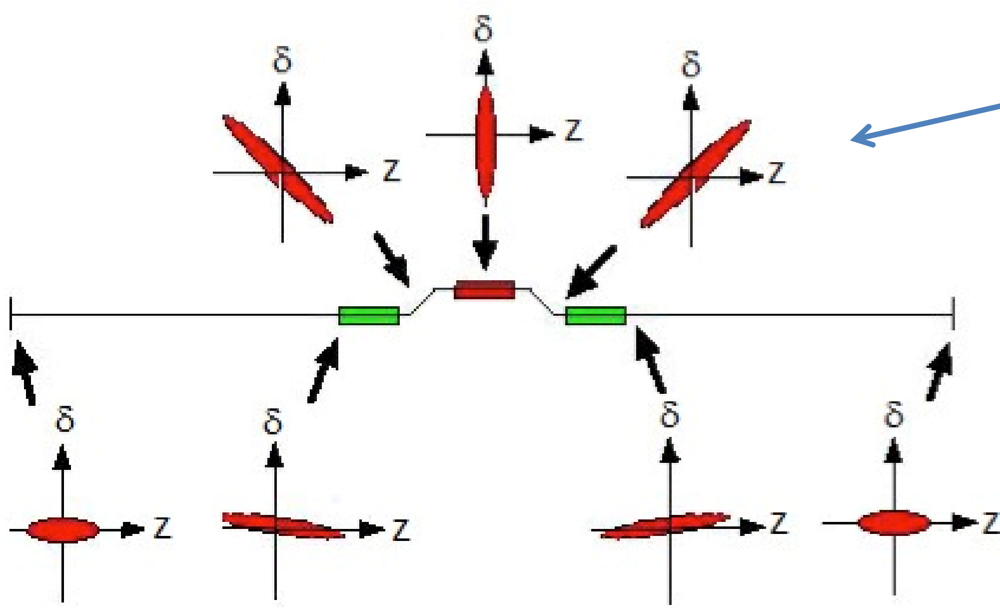
Only one undulator is needed if f_1 and f_2 are both within the undulator bandwidth.

4. Strong focusing SSMB

- To push up the harmonic generation h >> 1 requires intentional strong focusing. The energy spread and length of the microbunches vary around the ring. Stability of the microbunches requires

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

- The longitudinal phase space evolution of one microbunch over one superperiod:

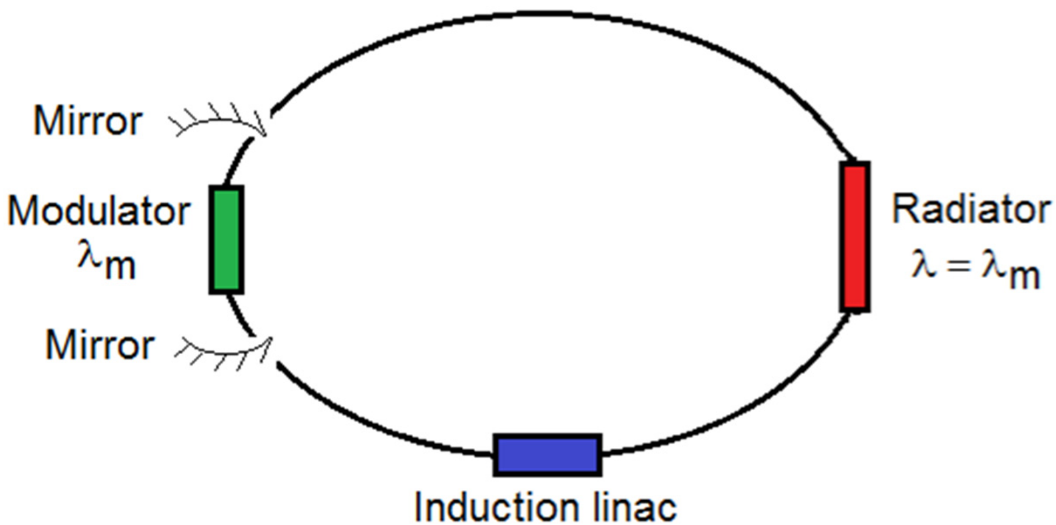


Harmonic generation

The beam distribution repeats turn-by-turn in steady state.

5. Amplifier SSMB

- Depending on applications, a relaxed SSMB with h=1 can use weak focusing.
- This SSMB serves as an amplifier of the seed laser.
- An induction linac serves as a pumping energy source.
- Example: with an EUV seed laser source, the scenario amplifies the EUV power.



Hardware for strong focusing SSMB

Storage ring

- ~ a few 100 MeV's (minimize collective effects)
- a small R_{56} per SSMB tool. The momentum compaction factor is $\alpha_c = n\, R_{56}/C$, with n SSMB tools in the ring. (Small ring is preferred.)
- NOT a low-emittance lattice (no need of high peak power) ➔ easier to reach low α_c

Two modulator undulators

- Each modulator contains an undulator (~2 m, 2 T) resonant with co-propagating seed laser λ_m.

Radiator undulator

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

Seed laser and mirrors

- Assume stored laser power in the laser cavity is limited at 1 MW.
- Required seed laser average power = 1 kW if the mirror reflectivity = 0.999.
- Synchronization of the seed laser phase is to be assured to an accuracy $< \lambda_m / 2\pi$.

Induction linac

- The power source for average beam acceleration is a solid state induction linac (~1 m, a few MHz, 10 kV).
- The induction pulse covers a fraction of the ring circumference of the filled beam.
- Multiple units can be used as needed to reduce the pulse repetition rate for each unit.

Strong focusing SSMB examples

		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
$\Delta\delta_{\mathrm{CSR}}$	CSR pot. well distort.	2.5	2.3	2.4	10^{-3}
τ_{RW}	resist.wall growth time	0.28	1.4	0.67	ms
$\tau_{\delta,\mathrm{IBS}}$	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_{stored}	laser stored power	1	1	1	MW
P_{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

SSMB can be scaled to IR, DUV, EUV. Tentative target radiation power ~ kW.

Coherent synchrotron radiation

The 1-D CSR stability threshold:

[Bane, Cai, Stupakov (2010)]

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

For all cases, we choose CSR threshold as the SSMB peak current limit.

The 2-D suppression of the CSR effect when $\sigma_x >> (\sigma_z^2\rho)^{1/3}$ is not taken into account.

Resistive wall instability

Single bunch instabilities are not serious.

Coupled bunch instabilities are a concern. Resistive wall:

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

Require feedback system. Power ~ a few watt narrow band.

Intrabeam scattering and diffusion

The IBS energy diffusion rate:

[Lebedev (2013)]

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

Require $\tau_{\delta,\,\mathrm{IBS}}$ > 3 x radiation damping times.

Seed laser

Stored seed laser power

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

We assume the limit of the mirrors is set by a maximum stored laser power at 1 MW. With mirror reflectivity 0.999, the required seed laser power is 1 kW.

Phase jitter is controlled to $< \lambda_m/2\pi$
(an advantage of SSMB: not $< \lambda/2\pi$)

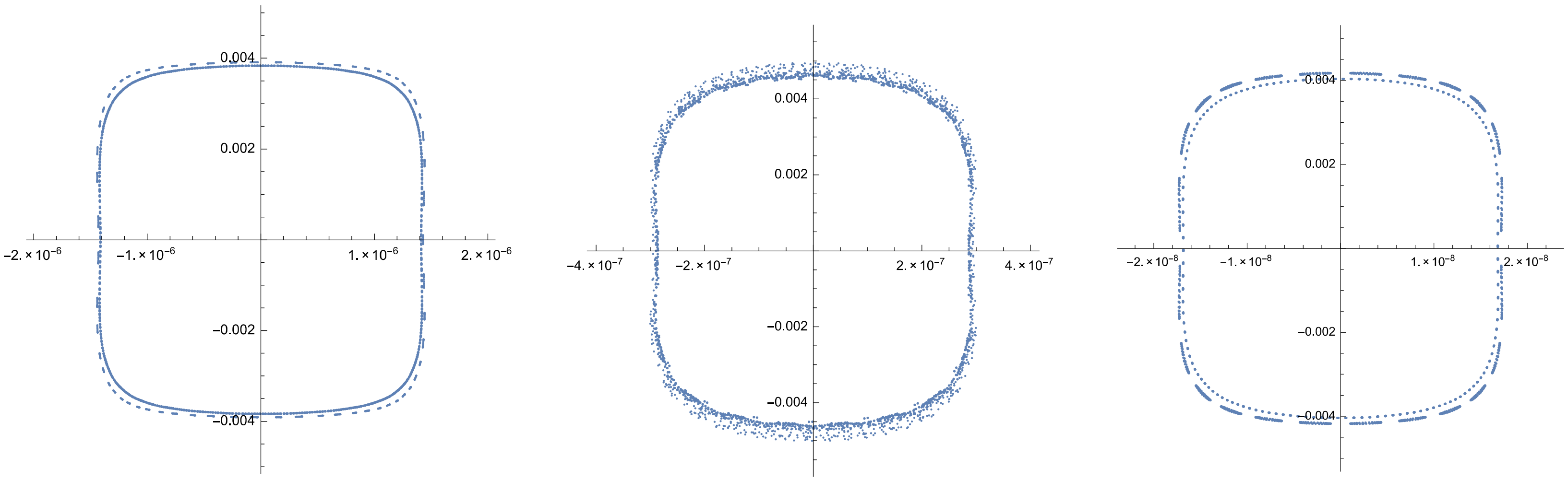
The laser system has a range of possibilities for further optimization. Options:

- divide the modulators into smaller pieces with reduced Rayleigh length
- over-moded laser waveguide to confine the laser
- dielectric laser acceleration
- self-seed the modulators without seed laser
- single shot seeding without mirrors

Stability of the microbunch buckets

The three cases are tracked for 1000 turns. To minimize the modulation nonlinearities, $\lambda_m \sim 20\ \sigma_z$.

Require 6σ stability region, maintaining sufficient quantum lifetimes.



Radiator

Radiation power

[Saldin, Schneidmiller, Yurkov (2005)]

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

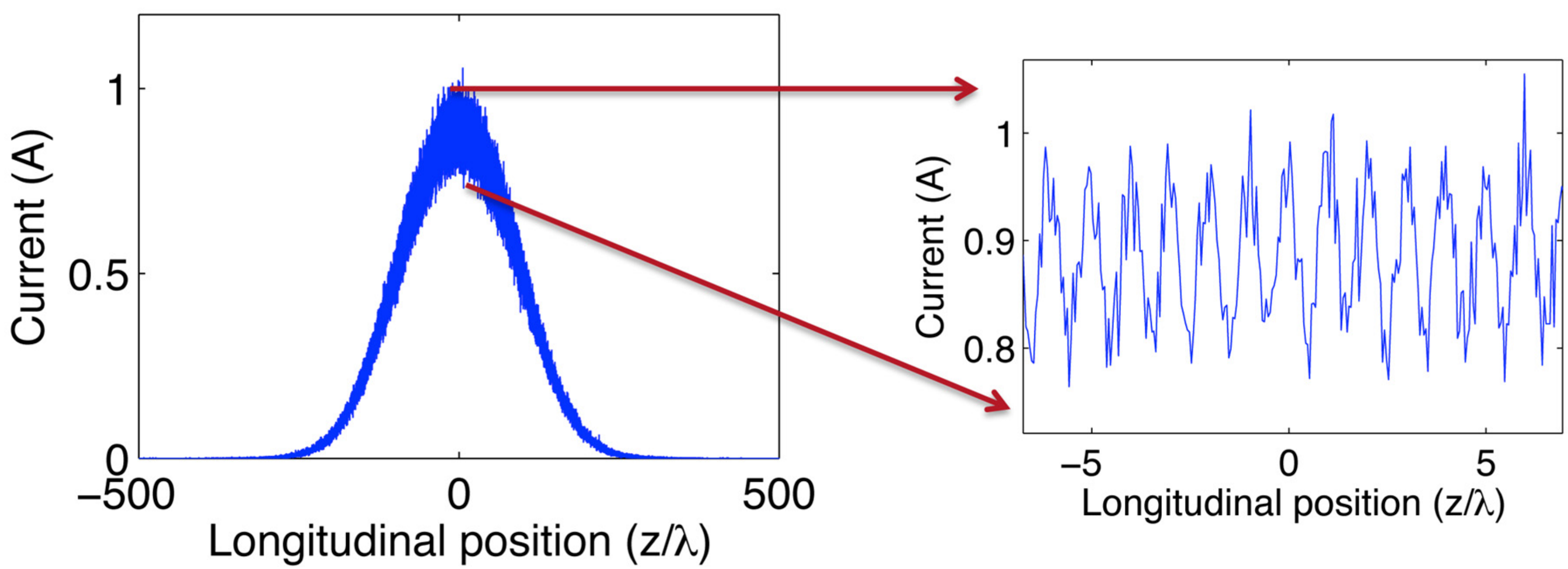
Proof-of-principle test proposal

Feasibility of SSMB has not been established experimentally. Suggest a proof-of-principle test for the weak focusing SSMB:

- A low energy storage ring
- Low α_C (SPEAR3 reached $\alpha_C = 3\text{x}10^{-6}$ at 3 GeV [Huang et al. (2007)])
- single RF bunch
- a single-pass laser (1 μm, 100 μJ, 1.5 MHz, no mirrors)
- beam is shallow microbunched at 1 μm without harmonic generation

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

- Simulation gives bunching factor ~5%
- Microbunching is detectable even at 0.5 μA beam current switching off the seed laser.
- Preliminary simulations indicate the phase jitter tolerance of 60^0 at jitter frequency of 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 factor of N_{coh} in the storage ring radiation power. Several SSMB scenarios have been proposed.

For applications that require both high average power and short wavelength, we concentrated on 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 work remains, 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.

The basic idea looks sound, and if accomplished, the rewards are high.

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