Steady State Microbunched Beam in a Storage Ring for EUV Radiation

6th Microbunching Instability Workshop, Alex Chao and Daniel Ratner

The mechanism of steady-state microbunching (SSMB) in storage rings is challenged for a 1-kW radiation source at 13.5 nm for lithography. Tentative conclusions:

- The SSMB mechanism should work. A SPEAR-like storage ring at low-α and low beam intensities can test the SSMB mechanism.
- To reach 1-kW with SPEAR, however, the beam intensity suffers from collective effects, particularly CSR.
- To reach the 1-kW goal: (a) an existing SPEAR-like ring operated with "staggered buckets", or (b) a new dedicated ring.

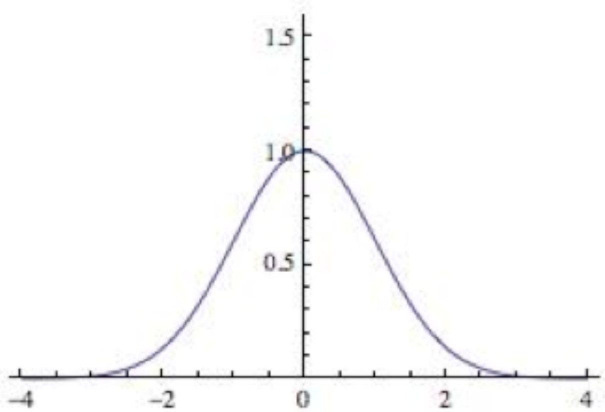
I. Motivation

Accelerators are powerful radiation sources. However, storage ring synchrotron radiation has low peak power, and pulsed linac FELs have low average power due to low repetition rates. Creative solutions:

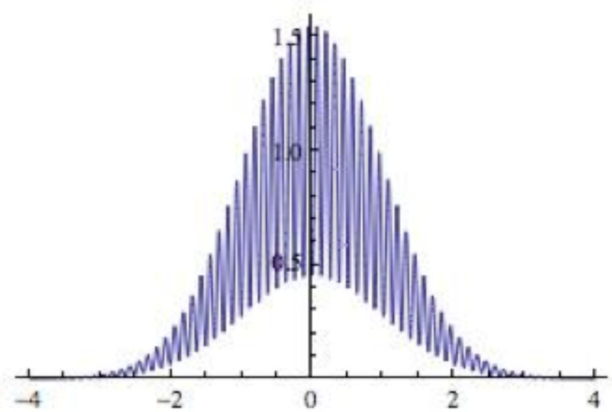
- superconducting CW linacs (K.J. Kim/Y. Shvydko/S.Reiche 2008; E.A. Schneidmiller et al. 2012; LCLS-II; Lithography Roadmap Consortium)
- energy-recovery linacs (J.M. Klopf et al. 2007)
- storage ring FELs (A. Renieri 1977; D.A.G. Deacon/J.M.J. Madey 1980; V.N. Litvinenko/S.F. Mikhailov/O.A. Shevchenko/Y. Wu 2001)
- SSMB (D. Ratner/A. Chao 2010, Jiao/Ratner/Chao, 2011)

The idea of SSMB is to manipulate the beam's longitudinal dynamics so that its steady-state distribution is not the conventional Gaussian, but microbunched.

Potential well = (original quadratic potential well + a microbunched potential well) so that the new Haissingski beam distribution acquires a SSMB steady state.



Normal beam - Gaussian



partially SSMB beam

The beam is microbunched every turn
$\Longrightarrow$ the beam radiates every turn
$\Longrightarrow$ high CW radiation power due to the high repetition rate.

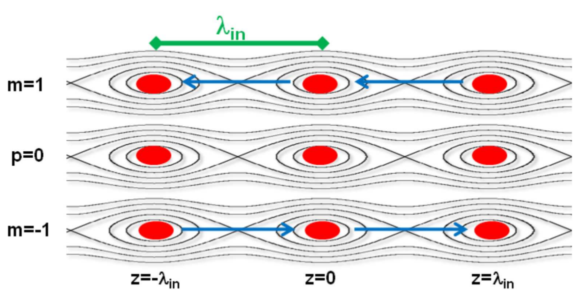
Radiation does not have to stop to wait for the beam to radiation damp every several passages.

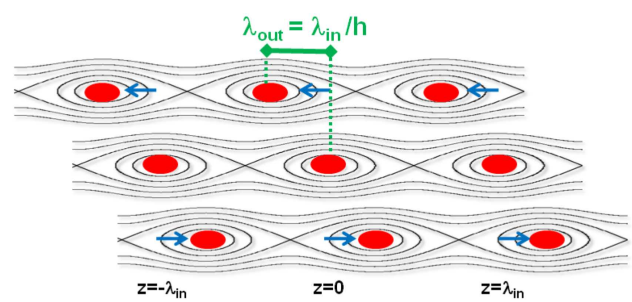
But the SSMB is only in principle. We now wish to apply it to a 1-kW 13.5-nm EUV source to see its potential and challenges.

II. Staggered Buckets

There are several ways to generate SSMB in a storage ring.

For example, using a seed optical laser to energy-modulate the electron beam $\Longrightarrow$ staggered buckets. The number of staggered bucket strings $h = 2A_\delta R_{56}/\lambda$ ($\pm A_\delta$ is the momentum aperture of the storage ring). Intensity per microbunch is reduced by h.

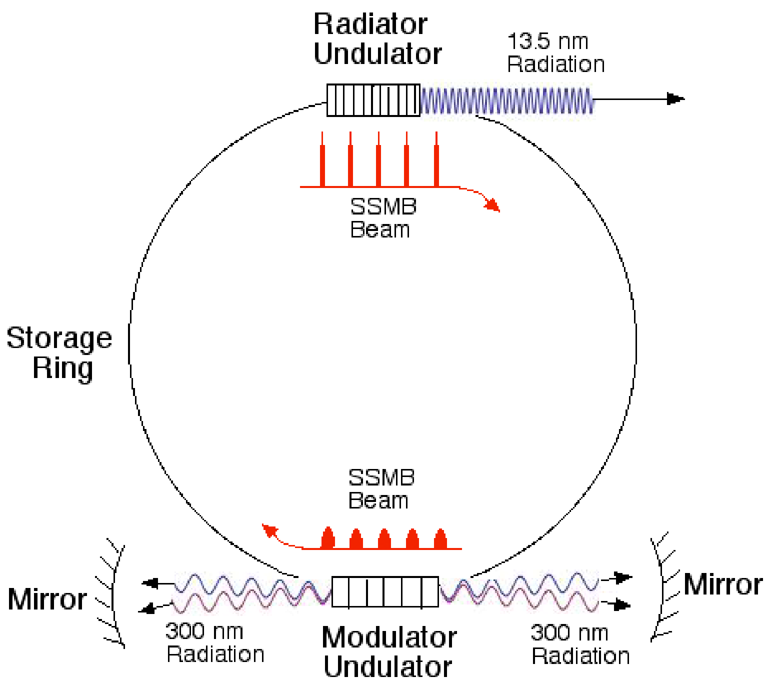




Staggered buckets as viewed at the modulation point (left), and as viewed 1/3 around the ring ($h = 3$) (right).

III. Outline of Device

We start without staggered buckets.



- A modulator (300 nm) and a radiator (13.5 nm) are installed in a storage ring with a low momentum-compaction.
- Seed laser is applied. The modulation is weak so that no significant SASE FEL has occurred in single passages.
- Mirrors are optional depending on available laser power.
- No FELs in this device.

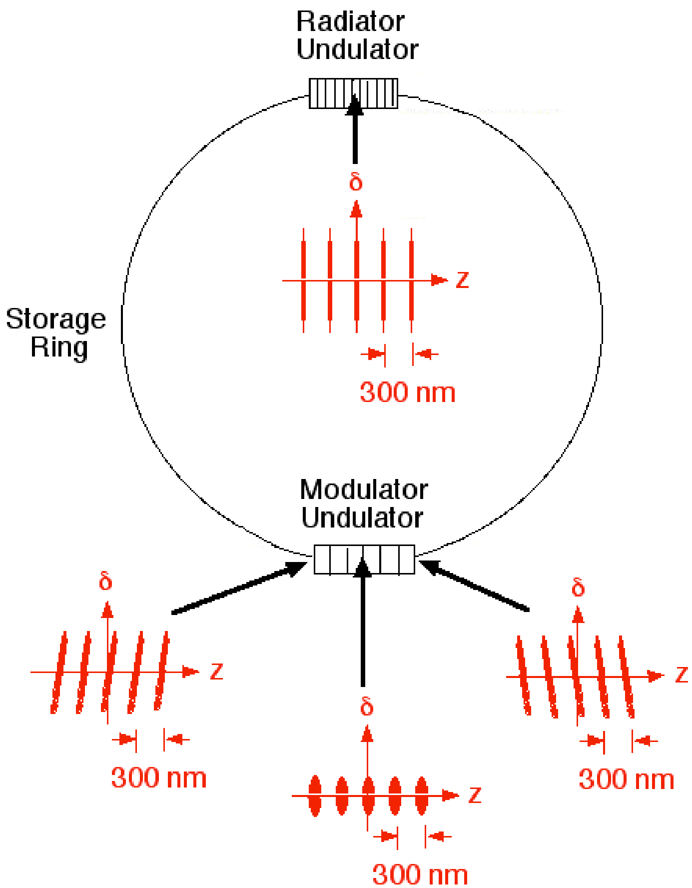
Spacing between microbunches is 300 nm at both undulators. But the microbunch lengths are different: 75 nm at modulator, 2.52 nm at radiator.

IV. The SSMB

The seed laser $\lambda = 300$ nm modulates the beam energy. If the storage ring has $R_{56} \approx 0$, microbuckets are formed. With radiation damping, the beam-radiation system reaches a SSMB state. The modulation amplitude $e\hat{V}$ and R_{56} constitute the microbunching longitudinal dynamics.

Each microbunch has a bunch center. Linearizing around these centers, applying Courant-Snyder formalism, we obtain microbunching synchrotron tune ν and longitudinal β_1 at the radiator:

$$\cos 2\pi\nu = 1 - \frac{R_{56}}{2f}, \quad \beta_1 = \frac{R_{56}}{\sin 2\pi\nu}\left(1 - \frac{R_{56}}{4f}\right), \quad \frac{1}{f} = \frac{2\pi e\hat{V}}{E_0\lambda}$$



Energy spread is determined by synchrotron radiation in the arc and the two undulators. We assume $\sigma_{\delta 1} = 3 \times 10^{-4}$.

Longitudinal phase space distribution of the microbunches:

- $\sigma_\delta = 3 \times 10^{-4}$ in radiator and arc, but $= 1.01 \times 10^{-5}$ at the center of the modulator.
- Bunching factor $B = 0.29$ at modulator, $B = 0.50$ at radiator.
- Straight sections of the two undulators are dispersion free.

Storage ring		
energy	1 GeV	
R_{56}	0.5 mm	
microbunch synchrotron tune ν	0.4893	
electrons per macro-bunch N_b	1.42×10^8	
peak electron current before SSMB	17 A	
peak electron current after SSMB	1.04 kA	
Undulator	modulator	radiator
resonant wavelength λ	300 nm	13.5 nm
period λ_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 β-function β_2, β_1	7.44 mm	8.41 μm
beam energy spread $\sigma_{\delta 2}, \sigma_{\delta 1}$	1.01×10^{-5}	3×10^{-4}
beam microbunch length σ_{z2}, σ_{z1}	75 nm	2.52 nm
bunching factor B	0.29	0.50
transverse rms beam size $\sigma_\perp$	120 μm	70 μm
peak radiation power	10.9 kW	2.33 MW
average radiation power	4.8 W	1.04 kW

To reach 1 kW, we assume the electron beam before microbunching has $I_p = 17$ A. When microbunched, it reaches 1.04 kA at the radiator.

Radiation power (E.L. Saldin/E.A. Schneidmiller/M.V. Yurkov 2004)

$$\widehat{P} = \frac{\pi^2 K^2 [JJ]^2}{2(2+K^2)} \frac{N_u N_b^2 B^2 m c^3 r_0}{L_z^2} F_n$$

where the diffractive transverse form factor

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

Radiation at the modulator: Assuming $\sigma_\perp = 120$ μm, we obtain peak power $\widehat{P} = 10.9$ kW. This radiation is directed to the dump.

V. The Seed Laser Power

The peak seed laser power per passage $\widehat{P}_{\text{seed}}$ needed for the required modulation voltage $\widehat{V} = 0.38$ MV is 2.2 kW or an average power is 0.97 W, if mirrors are used ($Q = 3000$).

Challenge is to hold a steady laser strength between the mirrors, with radiated power cleanly extracted. Alternatively, it is preferable to avoid mirrors, the seed laser needs to be 3000 times stronger.

VI. A High Power EUV Source

Radiation at the radiator: With $\sigma_\perp = 70\ \mu$m, radiation peak power = 2.33 MW and average power = 1.04 kW. Collective effects:

- The IBS energy spread diffusion time ~124 ms. Synchrotron radiation damping time = 53 ms.
- The energy distortion due to the CSR wake in the radiator $\gg \sigma_\delta \Longrightarrow$ disruption of the microbunching buckets. However, the very small longitidinal β-function at the radiator will help. More study is needed.
- If $A_\delta = 1.2\%$, we can stagger up to $h = 40$ microbunches. Beam intensity per microbunch can in principle be reduced substantially. CSR may be relieved this way.

- SASE at $I_p = 17$ 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, if large enough, can be a concern. Simulations are needed.
- To explore: 2D effects might reduce the CSR energy distorion? (R. Li talk); CSR self compensation with -I in longitudinl phase space by having superperiod = 4 ?

VIII. Test Proposal

SPEAR low-α operation reached $R_{56} = 0.92$ mm at 3 GeV. We assumed $R_{56} = 0.5$ mm at 1 GeV. If achievable (or otherwise using a double modulator scheme), SPEAR can be used to test the SSMB mechanism.

To reach 1 kW with SPEAR requires $I_p = 17$ A and $I_{\text{ave}} = 6$ mA. As mentioned, CSR in the radiator destroys the microbuckets. CSR compensation schemes or staggered buckets need to be developed and implemented if existing SPEAR has to be used.

IX. Dedicated Storage Ring ?

A dedicated ring will provide much needed flexibility. Examples of the parameters to vary:

- $R_{56} < 0.5$ mm can substantially relax the collective effects and the longitudinal lattice design
- X-band RF for more bunches
- longer bunches before microbunching
- control transverse beam emittances
- $\cdots$

X. Summary

The storage ring SSMB mechanism is challenged for a 1-kW CW EUV radiation source for lithography applications. The suggested test assimilates SPEAR lowest-α operation mode. 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.

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