An overview of the Steady State Microbunching R&D effort initiated at Tsinghua University

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  - MLS as an example and experiment on longitudinal physics
- A Brief Overview of other SSMB concepts
- PoP experiment of SSMB at MLS
- Summary
The power radiated in a storage ring:

\[ P(kW) = 88.47E^4(GeV)I(A)R^{-1}(m) \]

With an undulator: Power

\[ P_T[kW] = 0.633E^2[GeV]B^2[T]L[m]I[A] \sum \]

Resonant wavelength

\[ \lambda = \frac{\lambda_u}{2\gamma^2} \cdot 1 + \frac{K^2}{2} + \gamma^2\theta^2 \]

The typical power radiated in a storage ring is ~kW, and it will be much lower at a narrow band of a special wavelength.
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High rep-rate FEL based on SRF linacs and ERL

Electron Gun → Accelerating Structures → Undulators → Coherent radiations

Free Electron Laser

~us
High rep-rate FEL based on SRF linacs and ERL

*Saturation efficiency: 0.1-10%

Radiation Power at a very narrow bandwidth: ~10 kW

High rep-rate FEL based on SRF linacs and ERL

Saturation efficiency: 0.1-10%

Radiation Power at a very narrow bandwidth: \( \sim 10 \text{ kW} \)

The natural idea of SSMB is a scaling from microwave to optical, i.e., using laser modulator to replace RF to microbunch the beam and let it stay in a steady state.

Courtesy of Ratner & Chao
CSR based on SSMB ring

Small longitudinal $\beta$-function at radiator

Storage Ring

Energy

Time

Modulator

Dispersion

Modulator

EUV

$\sigma_{opt}$

$T_{opt}$

$\sigma_{EUV}$

Courtesy of Ratner & Chao

PRL 105.15 (2010): 154801
CSR based on SSMB ring

Small longitudinal $\beta$-function at radiator

Steady state micro-bunching!

Storage Ring

Radiator

Modulator

Dispersion

Energy

Time

$\sigma_{\text{opt}}$

$T_{\text{opt}}$

$\sigma_{\text{EUV}}$

Courtesy of Ratner & Chao

PRL 105.15 (2010): 154801
## CSR power of SSMB

### Shot Noise

\[ P_{\text{rad}} \propto \mu N_e \]

### Microbunching

\[ P_{\text{rad}} \propto \mu N_e^2 \]

### Compare SSMB with FELs and conventional storage rings:

<table>
<thead>
<tr>
<th></th>
<th>( f ) [GHz]</th>
<th>bunch length</th>
<th>microbunch length</th>
<th>( N_{\text{bunch}} )</th>
<th>( N_{\text{coh}} )</th>
<th>( fN_{\text{bunch}}N_{\text{coh}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv. storage ring</td>
<td>0.3</td>
<td>1 mm</td>
<td>&lt; 1 ( \mu )m</td>
<td>( 10^{11} )</td>
<td>1</td>
<td>( 0.3 \times 10^{11} )</td>
</tr>
<tr>
<td>Supcond. FEL</td>
<td>1</td>
<td>1 mm</td>
<td>&lt; 1 ( \mu )m</td>
<td>( 10^9 )</td>
<td>( 10^7 )</td>
<td>( 10^{16} )</td>
</tr>
<tr>
<td>SSMB</td>
<td>( 3 \times 10^5 )</td>
<td>&lt; 1 ( \mu )m</td>
<td>( 10^5 )</td>
<td>( 10^5 )</td>
<td>( 3 \times 10^{15} )</td>
<td></td>
</tr>
</tbody>
</table>

Courtesy of Ratner & Chao
Demands for High Average Power

- kW level EUV light source for lithography:

Moore’s law:
The number of transistors that could be fit on a chip of a given size at an acceptable cost doubles every two years.

- Denser integrated circuits → less power, lower cost
- Lithography → better resolution

\[ R = k \frac{\lambda}{NA} \]

- \( R \) is resolution,
- \( \lambda \) is wavelength,
- \( NA \) is numerical aperture,
- \( k \) is constant.

Advances in X-Ray/EUV Optics, Components, and Applications (2006)
Nature Photonics, 4(12), 809-811
Exciting Accelerator Physics of SSMB

- Dig the potential of longitudinal coherence of electron beam in electron storage rings;
- Longitudinal dynamics study, for example longitudinal strong focusing;
- Novel 3D phase space manipulation schemes;
- Many interesting effects which can be ignored in traditional storage rings;
- Collective effects study of steady state microbunches;
- ...
Current Status of SSMB Research

• Several different scenarios have been proposed and some preliminary theoretical study has been done since the first publication of the idea of SSMB;
• A dedicated taskforce has been established in Tsinghua University with the promote of Chao recently;
• Lattice design efforts of two SSMB approaches are being pursued in parallel by the collaboration:
  ➢ Strong focusing SSMB;
  ➢ Reversible seeding SSMB.
• PoP experiment is being prepared on MLS, the radiation source of the German national metrology institute (PTB).
• Low alpha + longitudinal strong focusing SSMB:
  ➢ Fist use low alpha lattice to reduce bunch length since \( \sigma_{z,\text{Sands}} \propto \sqrt{\alpha} \);
  ➢ Then apply longitudinal strong focusing to compress the bunch length further;

• Schematic configuration and the longitudinal phase space evolution of one strong focusing SSMB super-period:
The relation $\sigma_{z,\text{sand}s} \propto \sqrt{\alpha}$ breaks down when alpha approaches zero;

A stochastic fluctuations of where the photoemission takes place produces a fluctuation of path length of one revolution, thus resulting in a bunch length limit and an extra energy spread.

**Partial alpha:**

$$\tilde{\alpha}(s_j) = \frac{1}{C_0} \int_{s_j}^{\text{observation point}} \frac{\eta(s)}{\rho(s)} ds$$

Bunch Length Limit Caused by Partial Alpha

- Stochastic difference equation:

\[
\begin{pmatrix}
\frac{\delta E}{E_0} \\
\frac{\delta \tau}{\delta \tau}
\end{pmatrix}_n = A_{\text{damping matrix}} \begin{pmatrix}
\frac{\delta E}{E_0} \\
\frac{\delta \tau}{\delta \tau}
\end{pmatrix}_{n-1} + \begin{pmatrix}
\frac{\Delta E}{E_0} \\
\frac{\Delta \tau}{\Delta \tau}
\end{pmatrix}_n - \begin{pmatrix}
\langle \frac{\Delta E}{E_0} \rangle \\
\langle \frac{\Delta \tau}{\Delta \tau} \rangle
\end{pmatrix}
\]

where \(\delta\) means relative to the barycenter and \(\Delta\) means change in one turn.

- Equilibrium bunch length limit:

\[
\sigma_{z,lqe} = \sigma_{\delta,sands} C_0 \sqrt{I_\alpha}
\]

\[
l_\alpha = \frac{1}{C_0^2} \left( \int_{s_j}^{\text{watch point}} \frac{\eta(s)}{\rho(s)} ds - \langle \tilde{\alpha} \rangle C_0 \right)^2 \]
First Order Transverse Longitudinal Coupling

- Particles with different betatron amplitudes and phases pass bending magnets on different trajectories, resulting in longitudinal displacement differences and a bunch length limit (Shoji, Yoshihiko. PRSTAB 7.9 (2004): 090703):

\[
\delta L = \int_{s_s}^{s_s+L_0} [x(s)/\rho(s)] ds
\]

\[
x(s) = \sqrt{\varepsilon_{CSI} \beta(s) \sin \psi(s)}
\]

\[
\sigma_{hlc} = \sqrt{\varepsilon H}, \text{ with } H = \gamma \eta^2 + 2\alpha \eta' + \beta \eta'^2
\]
Second Order Transverse Longitudinal Coupling

- Oscillation amplitude based trajectory length is related to chromaticities due to symplectic condition (Etienne Forest. Beam dynamics, 1998):

\[ \Delta L_n = \int_{w}^{w+nL_0} \sqrt{(1 + \frac{x(s)}{\rho(s)})^2 + x'^2 + y'^2 - 1} \, ds \]

\[ \Delta C = \lim_{n \to \infty} \frac{1}{n} \Delta L_n = -2\pi (J_x \xi_x + J_y \xi_y) \]

Courtesy of J. Scott Berg
Second Order Transverse Longitudinal Coupling

• In a storage ring, the RF always makes sure the particle synchronize with it in average sense by longitudinal focusing. A shift of fixed point (synchronous) energy (momentum) will be introduced to fight against this path length shift (Shoji, Yoshihiko, et al. PRSTAB 8.9 (2005): 094001):

\[
\delta = - \frac{1}{\alpha_p} \frac{\Delta C'}{C_0}
\]

• Due to this effect, the energy spread will be enlarged by chromaticities in a low alpha ring.
Nonlinear Momentum Compaction

• Momentum compaction function:

\[ \alpha(\delta) = \alpha_0 + \alpha_1 \delta + \alpha_2 \delta^2 + \ldots \]

• When \( \alpha_0 \) approaches zero, the higher order terms will play bigger roles and transform the traditional RF-buckets to \( \alpha \)-buckets (Robin, David, et al. PRE 48.3 (1993): 2149.):

• It can be well controlled using sextupoles and octupoles to get a high enough bucket height to guarantee a long enough quantum lifetime.
Influences of Different Effects

• Until now, we have introduced several single particle effects important for strong focusing SSMB:
  - Longitudinal quantum radiation excitation;
  - First order transverse longitudinal coupling;
  - Second order transverse longitudinal coupling;
  - Nonlinear momentum compaction.

• To get a concrete feeling of these effects, we investigate their influences on MLS, the first low alpha storage ring optimized for coherent THz radiation (Feikes, J., et al. PRSTAB 14.3 (2011): 030705).

Poster: Xiujie Deng et, al. WEP2PT018
Metrology Light Source

Wüstefeld, Godehard, et al.
TU5RFP005, PAC09

Table 1: Main MLS Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>injection energy</td>
<td>105 MeV</td>
</tr>
<tr>
<td>max. energy</td>
<td>630 MeV</td>
</tr>
<tr>
<td>circumference optics</td>
<td>48 m</td>
</tr>
<tr>
<td>rf-frequency</td>
<td>4 cell double bend</td>
</tr>
<tr>
<td>max. rf-voltage</td>
<td>500 kV</td>
</tr>
<tr>
<td>hor. / vert. tune</td>
<td>3.2 / 2.2</td>
</tr>
<tr>
<td>short / long straight</td>
<td>2.5 m / 6 m</td>
</tr>
<tr>
<td>rms-bunch length</td>
<td>5 mm to 0.5 mm</td>
</tr>
</tbody>
</table>

Low alpha (1.3e-4) optics

Markus, PhD thesis, 2014
Longitudinal Quantum Radiation Excitation

• Bunch length limit caused by partial alpha on MLS is about $36\text{um}@630\text{MeV}$ at low alpha mode. It should be carefully treated in lattice design for EUV SSMB.

• This effect is caused by the dispersion in dipoles cooperated with the stochastic quantum radiation, possible ways to proceed:
  
  ➢ Minimizing dispersions at all dipoles;
  
  ➢ Lowering beam energy;
  
  ➢ Dividing the ring into $N_{iso}$ isochronous sections, the fluctuations of partial momentum compaction will be reduced by a factor of $N_{iso}^2$;
  
  ➢ Adopting the reversible seeding scheme for the EUV radiation.
First Order Transverse Longitudinal Coupling

• The largest bunch length limit due to 1st order horizontal longitudinal coupling on MLS is $450\text{um}@630\text{MeV}$ at low alpha mode, which means this effect can easily smear microstructures in many places of the storage ring.

• However, this effect can be helpful in some sense since very short bunch occurs only at specific locations and this will help mitigate the damages caused by collective effects like CSR and IBS (Courtesy of Markus Ries).
Strong Focusing Lattice Design of SSMB

Isochronous Unit Cell

Circumstance: 94m
Beam Energy: 400MeV
Momentum Compaction: $1e^{-7}$

Two-stage micro-bunching:
$1^{\text{st}}$ stage $\rightarrow$ 100nm, $2^{\text{nd}}$ stage $\rightarrow$ 1nm
Dedicated Lattice Design

- Minimize the effect of longitudinal quantum radiation excitation by canceling the momentum compaction within each dipole.

- Abandon the achromatic condition to make chromaticity correction not too hard.

Poster: Tenghui Rui et, al. WEP2PT014
• Low dispersion and small beta function at most places combined lead us to a low emittance ring.

• Dispersion suppression section for insertion devices to avoid the first order horizontal longitudinal coupling.
Comparison with MLS

• Bunch length limit caused by longitudinal radiation excitation:
  - MLS: 36um@630MeV
  - Dedicated design: 500nm@630MeV

• Largest bunch length limit caused by 1st order coupling:
  - MLS: 450um@630MeV
  - Dedicated design: 8um@630MeV

• Nonlinear momentum compaction terms are under optimization;

• As mentioned earlier, to reach EUV radiation, a strong focusing cell is needed in addition.
A sketch of strong focusing SSMB EUV light source
Storage Ring Dedicated for SSMB

Main Parameters
- Circumference: 94m
- Beam Energy: 400MeV
- Momentum Compaction: <1e-7m
- Two-stage micro-bunch generation
  - 1st stage: ~100nm
  - 2nd stage: ~1nm

Main Components
- Modulator
- Radiator
- Kicker
- Induction linac
- Injection/Extraction Septum Magnet

Main Structures
- Isochronous unit cell
- Conventional undulator buncher
- Undulators for Longitudinal strong focusing
It can be anticipated **coherent synchrotron radiation** and **intra beam scattering** will be the two dominant collective effects since now we have short bunch and low emittance at the same time.

As a result of these considerations, the number of electrons per microbunch is limited to about **4000** in the present design.

**Future work:**

- Optimization of higher orders of the momentum compaction;
- Detail design of the longitudinal strong focusing cell;
- Simulation of microbunching with dynamic aperture effect.
Reversible seeding SSMB

- Few additional requirements (no need of low alpha) on the lattice outside of the insertion since the beam microbunches only within the radiator;
- Careful design to realize perfect cancellation of the seeding module.

Ratner, Daniel, and Alex Chao. No. SLAC-PUB-14718. 2011.
A Novel Seeding Method

• Making full use of the characteristic that the vertical emittance is much smaller than the horizontal one in usual storage rings to realize large bunching factor with small energy modulation.

Proof-of-principle Experiment

• Realize EUV SSMB need careful dedicated work, the first step would be a single pass experiment to verify some basic ideas of SSMB and study related physics.

• Steps:
  ✓ Let beam reach natural state;
  ✓ Use a laser modulator to energy modulate the beam;
  ✓ The microbunches formed one turn later will radiate coherently at the modulation wavelength.
Purpose of the proof-of-principle Experiment

• Verify microbunches can be formed and survive after traversing the whole ring;
• Realize amplification of the modulation laser power by the coherent radiation one turn later, proving the SSMB amplifier scenario;
• Study parameters and effects influencing the decay (smearing) rate of microstructures which would also be important for true SSMB;
• Since the test is to be performed using IR laser, its success would be readily applicable to an IR SSMB with applications of its own without having to push towards EUV.
Example Experiment Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>250 MeV</td>
</tr>
<tr>
<td>Momentum Compaction</td>
<td>$2 \times 10^{-5}$</td>
</tr>
<tr>
<td>Modulation Laser Wavelength</td>
<td>800 nm</td>
</tr>
<tr>
<td>Modulation Laser Peak Power</td>
<td>500 kW</td>
</tr>
<tr>
<td>Undulator Parameter</td>
<td>2.05</td>
</tr>
<tr>
<td>800 nm Bunching Factor One Turn Later</td>
<td>0.25</td>
</tr>
<tr>
<td>Peak Current Needed For Amplification</td>
<td>48 A</td>
</tr>
</tbody>
</table>

- Peak current needed for amplification is beyond the present reach of MLS and methods to lower this requirement is under study.
• An SSMB taskforce has been established in Tsinghua University.
  - Strong focusing and reversible seeding are the two schemes on which the team focuses and good progresses have been made;
  - Another main task now is the PoP experiment prepared to better understand physics related to SSMB.

• We have enlisted the technical challenges envisioned for the EUV SSMB, most of which comes from the short EUV wavelength. Challenging as it is, however, EUV SSMB offers an exciting area of research and the reward would be tremendous if realized.
The Collaboration Team