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AN OVERVIEW OF THE PROGRESS ON SSMB

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Abstract

Steady State Microbunching (SSMB) is an electron storage ring based scheme proposed by Ratner and Chao to generate high average power coherent radiation and is one of the promising candidates to address the need of kW level EUV source for lithography. After the idea of SSMB was put forward, it has attracted much attention. Recently, with the promote of Chao, in collaboration with colleagues from other institutes, a SSMB task force has been established in Tsinghua University. The experimental proof of the SSMB principle and a feasible lattice design for EUV SSMB are the two main tasks at this moment. SSMB related physics for the formation and maintenance of microbunches will be explored in the first optical proof-of-principle experiment at the MLS storage ring in Berlin. For EUV SSMB lattice design, longitudinal strong focusing and reversible seeding are the two schemes on which the team focuses. The progresses made as well as some challenges from physical aspects for EUV SSMB will be presented in this paper.

INTRODUCTION

Storage ring based synchrotron radiation facilities and linac based free electron lasers are the main workhorses of nowadays accelerator light sources and deliver light with characteristics of high repetition rate and high peak power respectively. However, there are some applications demanding high average power. One example is the kW level 13.5 nm EUV source needed by semiconductor industry for lithography. To generate high average power radiation, high repetition rate or high peak power alone is not enough, we need to combine both. This hope of combination leads to the idea of SSMB [1], i.e. microbunching in a steady state, microbunching for high peak power and steady state for high repetition rate.

It can be seen from the introduction above that SSMB is a general concept and there are several different specific scenarios proposed since the first publication. Interested readers may read [1-5] for more details about these scenarios. As a new accelerator physics idea, SSMB has attracted a lot of attention. Recently, with the promote of Chao, in collaboration with colleagues from other institutes, a SSMB task force has been established in Tsinghua University with a final goal of kW level EUV source. The two main tasks at this moment are the experimental proof of the SSMB principle and a feasible lattice design for EUV SSMB. The PoP experiment is planned based on the Metrology Light Source (MLS) [6], the radiation source of the German national metrology institute (PTB). The possibility of conducting the experiment on MLS is being carefully evaluated. For the eventual EUV SSMB lattice design, longitudinal strong focusing and reversible seeding are the two schemes being pursued by the team. The progresses made as well as challenges encountered in the study will be given below.

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STRONG FOCUSING SSMB

The natural idea of SSMB is a scaling from microwave to optical, i.e. using laser modulator to form optical buckets to microbunch the electron beam just like using RF to bunch electron beam in traditional storage rings.

One of the SSMB lattice scheme is the longitudinal strong focusing scheme. In the strong focusing scheme, a low alpha lattice is needed to let the beam microbunch in the optical buckets in a steady state. However, it is difficult to realize nm level microbunches needed for coherent EUV radiation by applying low alpha lattice alone due to challenges to be introduced momentarily. Longitudinal strong focusing will be applied to compress the bunch length further for coherent EUV generation. Two modulators sandwiching one radiator will play the role of longitudinal strong focusing not unlike the function of final focusing cell in a collider on the transverse dimension. Figure 1 shows the schematic configuration and the longitudinal phase space evolution of one strong focusing SSMB super-period.

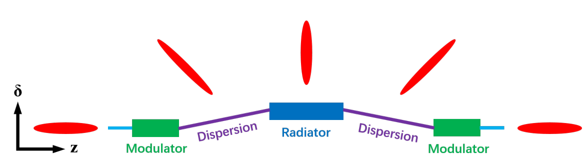

Figure 1: One super-period of longitudinal strong focusing.

In the reversible seeding scheme [3], on the other hand, there is no need of a low alpha lattice. The reversible seeding scheme is also investigated by the collaboration. We will start with the introduction of strong focusing SSMB.

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Longitudinal Quantum Radiation Excitation

The reason we need low alpha lattice for the strong focusing scenario is based on the famous "zero current" bunch length formula $\sigma_s \propto \sqrt{\alpha_p}$, in which α_p is the momentum compaction function of the ring. It seems the bunch length can be as short as we want as long as α_p can be tuned as small as possible. But this formula breaks down when α_p approaches zero since the quantum excitation should then be considered more carefully. A zero α_p does not necessarily guarantee a very short electron bunch. An effect called longitudinal quantum radiation excitation [7] and a quantity called partial momentum compaction or partial alpha become more important in this situation. The definition of partial alpha is

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

in which s_j is the point of photon emission and C_0 is the circumference of the ring. Even if α_p of the whole ring is zero, the fluctuation of partial alpha would still be unavoidable. A stochastic fluctuation of where the photo emission takes place then produces a fluctuation of path length of one revolution, thus resulting in a bunch length limit [7]

$$\sigma_{lqe} = T_{rev}\delta_{EN}\sqrt{I_\alpha} \qquad (2)$$

where I_α is the variance of partial alpha, T_{rev} and δ_{EN} mean the revolution period and the conventional natural energy spread respectively. The physical picture of this effect is shown in Fig. 2.

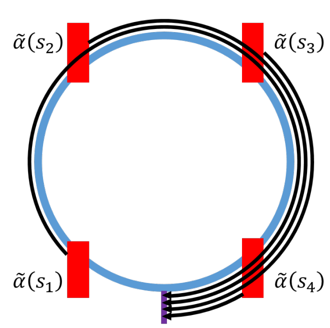

Figure 2: Partial alpha and longitudinal quantum radiation excitation.

Quantitative calculations and particle tracking show that the bunch length limit caused by this effect on MLS is about 36 µm when operated at 629 MeV low alpha mode [8], which means this effect should be carefully treated when doing EUV SSMB lattice design. It can be seen from the above analysis this effect is caused by dispersions at the dipoles cooperated with the stochastic quantum radiation. In order to lower this bunch length limit, possible solutions are:

- Minimizing dispersions at all dipoles;
- Lowering beam energy;
- Dividing the ring into N_{iso} isochronous sections, the standard deviation of partial alpha will be reduced by a factor of N_{iso}^2;
- Adopting the reversible seeding scheme for the EUV radiation.

Transverse Longitudinal Coupling

To generate 13.5 nm EUV coherent radiation, we need microbunch of about 2 nm which is much shorter than that can be reached in most existing storage rings. Many effects which can be ignored in traditional storage rings may play a vital role when we push the bunch length to such a small value. One example is the longitudinal quantum radiation excitation introduced above. Another effect is the transverse longitudinal coupling. The coupling effect can further be divided into the 1^{st} order [9] and the 2^{nd} order [10]. In this paper, we focus on the 1^{st} order horizontal longitudinal coupling and the 2^{nd} order coupling effect will be treated in a separate paper being prepared.

The 1^{st} order horizontal longitudinal coupling effect is easy to understand. Particles with different betatron amplitudes and phases pass bending magnets on different trajectories, resulting in longitudinal displacement differences and a bunch length limit [9]

$$\sigma_{hlc} = \sqrt{\varepsilon H},\ with\ H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2 \qquad (3)$$

It can be seen from Eq. 3 this bunch length limit oscillates around the ring according to the square root of the product of horizontal emittance and chromatic H function. The biggest value of this limit on MLS is about 450 µm when operated at 629 MeV low alpha mode, which means the influence of this effect can be much larger than that caused by longitudinal quantum radiation excitation at some places. We need to place the radiator at a dispersion free section to make this limit equal zero. 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 coherent synchrotron radiation and intra beam scattering.

Nonlinear Momentum Compaction

To store the microbunches steadily in optical buckets, a very small momentum compaction of the ring is needed in the strong focusing scenario. Momentum compaction of a ring is actually a function of the energy deviation

$$\alpha(\delta) = \alpha_0 + \alpha_1\delta + \alpha_2\delta^2 + \ldots \qquad (4)$$

When we push the momentum compaction to a value close to zero, the higher orders of the momentum compaction function will play a bigger role and transform the traditional RF bucket to α-bucket. This longitudinal nonlinear dynamics has been well studied by many authors and it is known the higher order terms should be lowered at the same time when we push α_0 to a small value to maintain high enough bucket height and long enough quantum life time [11]. Careful lattice design should be conducted to accomplish this.

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This requirement may potentially have some conflicts with the need of longitudinal chromaticity which relates to the higher order momentum compaction terms for longitudinal head-tail instability suppression and further study is needed to evaluate the influence.

Preliminary Lattice Design

It is obvious from the analysis above dedicated lattice design is needed for EUV SSMB. Some attempts have been tried by the collaboration and the layout of the preliminary lattice design is shown in Fig. 3. More details will be implemented with the research going on.

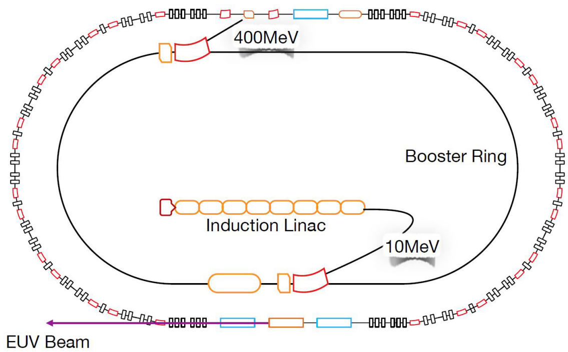

Figure 3: Layout of a SSMB optimized storage ring.

The circumference of the ring is 94.2 m and the main structures are the non-achromatic isochronous cells shown in Fig. 4. The lattice functions are calculated and plotted by Elegant [12]. This cell minimizes the effect of longitudinal quantum radiation excitation by canceling the momentum compaction in a single dipole which means the dispersion function crosses zero within the dipoles. The reason of abandoning the achromatic condition in usual lattice design is otherwise chromaticity correction would be too difficult. The low dispersion and small beta function of this design combined lead us to a low emittance ring.

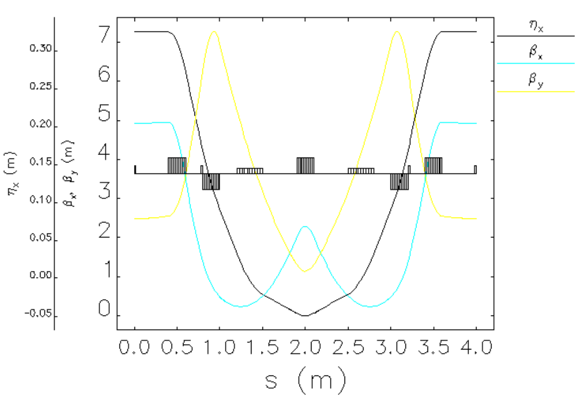

Figure 4: Non-achromatic isochronous cell.

As analyzed previously, the radiator should be placed at a dispersion free straight section to avoid the 1^{st} order horizontal longitudinal coupling. A separate dispersion suppression cell matching the non-achromatic isochronous cell is needed for insertion device, which is shown in Fig. 5.

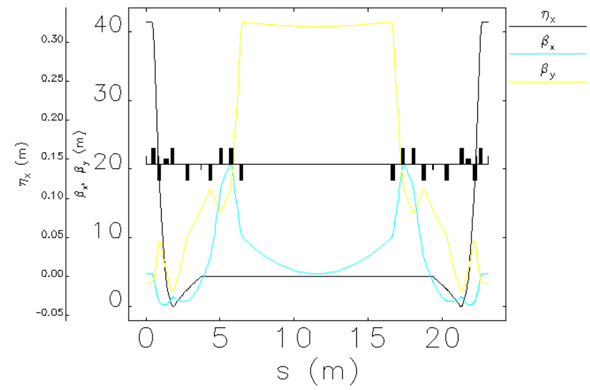

Figure 5: Dispersion suppression cell.

This dedicated lattice design has largely suppressed the bunch length limit caused by the longitudinal quantum radiation excitation, more quantitatively it is about 80 times smaller than that on MLS if operated at the same energy. As mentioned earlier, to reach EUV radiation, a strong focusing cell is needed in addition, as illustrated in Fig.1. The realization of this cell is under study. More details about the lattice design can be found in [13].

Collective Effects

For collective effects, some preliminary theoretical analysis has been conducted in previous research [5]. More in-depth study is continuing. It can be anticipated coherent synchrotron radiation and intra beam scattering will be the two dominant ones 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.

REVERSIBLE SEEDING SSMB

As introduced earlier, the reversible seeding as a promising scheme is also investigated by the collaboration. It is conceptually the easiest approach and has few additional requirements on the lattice outside of the insertion section. The beam only microbunches within the radiator after modulation and dispersion and then restores to the normal state due to the opposite dispersion and reverse modulation process following the radiator. This reversible seeding scheme does not require low alpha lattice. But its seeding module would however need careful design to realize perfect cancellation.

The application range of this approach is determined by the wavelength of the seeding laser available and the harmonic number can be reached. In order to get significant bunching factor at 13.5 nm, which means the 20^{th} harmonic if we use 270 nm laser as seed, clever seeding skill should be used. The team adopts a recently proposed scheme [14] which makes full use of the characteristic that the vertical emittance is much smaller than the horizontal one in usual electron storage rings. A large bunching factor of

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high harmonic number can be realized with a small energy modulation since the energy modulation strength of a particle is correlated to its vertical slope y' in the modulation process. For further information about the progresses on the reversible seeding SSMB, readers are encouraged to read [15].

PROOF-OF-PRINCIPLE EXPERIMENT

Careful work is needed to realize SSMB due to challenges introduced. The first step would be a single pass proof-of-principle experiment to verify some basic ideas of SSMB. The PoP experiment is now planned to be conducted on MLS, the first storage ring optimized for generating coherent THz radiation [6]. Figure 6 shows the layout and some basic parameters of MLS. By applying a sextupole and octupole correction scheme, MLS is capable of reliable tuning of the low alpha optics, which is important for the PoP experiment.

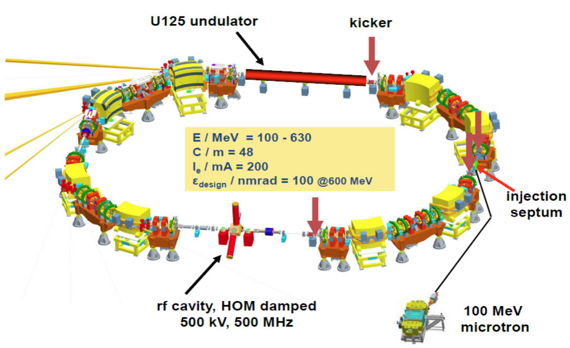

Figure 6: Layout of MLS.

The steps of the experiment would be:

- First let the electron beam reach natural equilibrium state;
- Then use the laser modulator to energy modulate the beam;
- The whole ring will play the role of a dispersive section converting energy modulation to density modulation;
- The microbunches formed one turn after modulation will radiate coherently at the modulation wavelength.

The goals of the experiment are:

- Verify microbunches can form and survive after traversing the whole ring;
- Realize amplification of the 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;
- Explore other potential related issues.

The final optimized choice of parameters is still under study. One example set of parameters is shown in Table 1. It can be seen there is significant bunching at the modulation wavelength one turn later after modulation and it can be expected coherent radiation with the same wavelength will be generated by the microbunches traversing the undulator. However, the peak current needed for amplification is beyond the present reach of MLS and methods to lower this requirement are being investigated.

Table 1: Example Choice of Parameters

Parameter	Value
Beam Energy	250 MeV
Momentum Compaction	2×10^{-5}
Modulation Laser Wavelength	800 nm
Modulation Laser Peak Power	500 kW
Undulator Parameter	2.05
800 nm Bunching Factor One Turn Later	0.25
Peak Current Needed For Amplification	48 A

CONCLUSION

A SSMB task force has been established in Tsinghua University collaborated with colleagues from other institutes and the SSMB research is being steadily pushed forward. As for the final goal of EUV SSMB, two schemes namely the longitudinal strong focusing and the reversible seeding are being studied in parallel by the team and good progresses have been made. More further work is needed to realize a feasible lattice design. The other main task namely a PoP experiment with the aim to better understand the physics related to SSMB is also being planned and prepared.

We have enlisted the 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.

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