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A Compact High-Power Radiation Source Based on Steady-State Microbunching Mechanism

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Abstract An initial collaboration is being formed at the Tsinghua University, Beijing, to design a compact electron storage ring that incorporates the Steady-State Microbunching (SSMB) mechanism for the purpose to generate high-power CW radiation in the frequency range from IR to EUV. In this talk, the principle of the SSMB is briefly reviewed and the status of the design effort presented, focusing on the specific application to an EUV source.

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1 Introduction

A steady-state microbunching (SSMB) mechanism [1] was introduced to produce high-power CW radiation for wavelengths ranging from IR to EUV, and also in the wavelength of THz. Here in this talk, we focus on only the EUV radiation for applications to industrial lithography of chip production. For these applications, it appears that there is the need of an EUV radiation source with the following properties:

- High average power: The power aimed is > 1 kW per tool. Each facility should be able to incorporate multiple tools.
- Truly continuous wave: The temporal structure of the radiation should have a smooth, CW structure, and not pulsed with peaked structures. This minimizes the chip damage problem.
- Narrow banded: The radiation should have a frequency bandwidth < 1% to match the required high reflectivity of the mirrors.
- Collimated: The radiation should have a well collimated angular spread $\lesssim 0.1$ mrad. The required multi-layered mirrors become fewer in number and much smaller in size.
- Stability: The radiated spot at the wafers should be steady so that the power delivered stays within < 1%.
- Clean radiation: The radiation should be clean and carries no debris, so that mirrors do not get contaminated and do not require frequent replacements during operation.
- Low power consumption.

The present EUV sources fall substantially short of the targeted high power, and even a compromised power has been reached without meeting some of the other requirements. In this talk, we introduce the SSMB approach. We are presently only at an R&D stage of the SSMB. However, if realized, its radiation is expected to be truly CW, narrow banded and collimated, yielding an ideal, clean, high-power radiation source [1, 2].

The EUV radiation is to be transported to the wafers by a large number (~ 10) of multi-layered mirrors. The clean radiation from SSMB leads to a substantially higher collection efficiency of the radiation to the wafers, so fewer mirrors will be needed. Since each mirror means a loss of approximately 30% of the radiation power, reducing the number of mirrors means the 1 kW power allows a substantially higher radiation dosage actually delivered.

At present, SSMB is under R&D by a collaboration hosted at the Tsinghua University, Beijing. The collaboration is informal and academic, and is joined by participants from several interested institutions. A pilot test is being considered at Metrology Light Source (MLS), Berlin [3]. In this talk, we will briefly discuss the mechanism of the SSMB, then we briefly mention the present R&D efforts



Figure 1: A strong focusing SSMB insertion and a storage ring with two such insertions.

by the collaboration and the envisioned plan for the pilot test. A status of this effort was reported earlier in [4].

2 Sketch of an SSMB Facility

Let us first give a quick sketch of an SSMB facility. An SSMB facility aims to produce high-power radiation at some desired wavelength. It consists of a storage ring with energy in the range of 400 MeV to 1 GeV, circumference of 50-100 m, and 2-6 radiation tools properly spaced along the circumference.

Each tool is an insertion of several meters length in the storage ring beamline. For the EUV case, the tool insertion consists of three undulator magnets. (For radiation of longer wavelengths, the insertion can be simpler.) A laser system with a laser cavity is installed with its stored laser going through two of the three undulators. This laser system uses a laser of IR wavelength — not an EUV wavelength — and is referred to as the seed laser. The third undulator serves as a radiator, where the EUV radiation of 1 kW is to be extracted. A sketch of this insertion section and a storage ring facility with two tools are shown in Fig. 1. The green elements are the "modulator undulators". The red ones are the "radiator undulators". The IR laser goes through the modulator undulators. EUV radiation comes off the radiator undulator.

An undulator is a device consisting of a packed periodic array of dipole magnets with alternating polarities. The choice of the undulator parameters are such that they match a certain laser wavelength λ according to

$$\lambda = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right)$$

where λ_u is the period length of the undulator dipoles, γ is the Lorentz factor of the electron beam, and $K = \frac{eB_u\lambda_u}{2\pi mc}$ with B_u the undulator dipole field. In the modulator undulator, λ is chosen to be the wavelength of the IR seed laser. In the radiator undulator, it is the EUV wavelength.

With the installation of a seed laser system, there is in principle no need of an RF system in the SSMB ring. In this case, however, the EUV radiation power would be extracted from the power of the IR seed laser. Although not a problem in principle, this is a costly arrangement. We propose to use a flat top induction linac to be the power source. In this case, the EUV power comes from the induction linac. The induction linac voltage is very low, ≤ 10 kV, as compared with the seed laser modulation voltage \sim MV. On the other hand, the induction voltage has the high repetition rate as the circulation period of the storage ring, and has to be steady pulse after pulse. A compact solid state induction linac is envisioned.

The envisioned facility is compact, and is expected to be very cost effective for such a high-power EUV source. But as mentioned, it is currently in the R&D stage, not available as an industrial production tool. The present R&D status will be mentioned later in this report. Limited by available resources, the R&D progress has been steady but slower than ideal.

Figure 1 is in fact a sketch of only one of the two SSMB schemes proposed for EUV radiation. It is called a "strong focusing" SSMB scheme. There is another "reversible SSMB scheme", which we will touch upon as well later.

3 The SSMB Mechanism

The SSMB mechanism is based on an extension of the conventional electron storage rings. It applies the same established practices of the conventional storage rings, but the required extension is challenging. Basically, the conventional radio-frequency system is replaced by an IR seed laser system. The bunches spaced by the RF wavelength are now spaced by the IR wavelength. The number of bunches therefore increases by about six orders of magnitude. Each bunch becomes very short, and is now referred to as a microbunch.

The design of an SSMB facility, therefore, basically we follow the same design steps as we do for a conventional electron storage ring and calculate the equilibrium beam distribution as a balance between quantum excitation and radiation damping. This equilibrium state does not invoke other mechanisms (especially and specifically not the FEL mechanism). With the RF replaced by laser, the beam will be microbunched naturally. What we need to do is to make sure that all the conventional accelerator physics rules are all obeyed, such as collective instabilities, lattice designs, quantum lifetimes, etc. By an additional arrangement indicated by the two chicanes (labelled as R_{56} in Fig. 1) around the radiator undulator, these microbunches are temporarily "strong focussed" to become even shorter at the radiator undulator, so that they now *coherently* radiate the EUV radiation at the radiator.

The coherence of the radiation is the key to its high radiation power. The power gains a factor of $N_{\rm coh}$ due to this coherence property, where $N_{\rm coh}$ is the number of coherent electrons in the microbunches and their neighbors.

The microbunches are highly peaked, and due to the chicanes, are even more peaked temporarily at the radiator. One must deal with all the known collective instability effects associated with these highly peaked microbunches. These instabilities have been taken into account in the present design efforts. For these reasons, the proposed beam for EUV, for example, is conservatively chosen to have a very low intensity of 4000 electrons per microbunch (see Table 1 later). This very low intensity of microbunches, while reaching 1 kW radiation power, is made possible also because we use an induction linac as the power source. With a long flat top, the beam train stretches long, thus spreading the beam into many microbunches. In addition, it makes the radiation truly CW.

The purpose of the modulators is to microbunch the electron beam. The mechanism is the same as that of bunching in a conventional storage ring by the RF system, only that the long wavelength RF is replaced by the short wavelength IR laser. The pairing of the modulators sandwiching the radiator is so that a strong focusing action is introduced so that extra short microbunches are temporarily produced at the radiator for the purpose of radiating EUV radiation. For radiation with wavelength longer than the EUV, the strong focusing complication can be removed, making a much simpler SSMB insertion.

Once microbunched, the microbunching also has to be maintained in a steady-state, i.e. the electron beam must keep its microbunched structure turn after turn as it circulates around the storage ring. This is so that the beam can radiate at every turn of its passage through the radiator, thus achieving a 1 kW average power. Without the steady state condition, it is impossible to reach this power level according to our analysis.

As mentioned, SSMB does not invoke any FEL mechanism. In comparison, the approach of "storage ring FELs" [5] and some of their more recent variations that invoke FEL mechanism for the EUV radiation encounter the limitation due to energy heating [6]. These FEL-based approaches do not impose the steadystate condition, and are not SSMB devices. They offer higher peak power but the electron beam is disrupted after each passage and needs radiation damping to recover. Although implemented in a storage ring, they are in reality singleshot devices; the high repetition rate of a storage ring is not utilized, losing a few orders of magnitude in the resulting radiation power in the process. FELs are high-peak-beam-current devices, and are intrinsically non-steady-state, thus in sharp contrast with the SSMB. This stage of "MB without SS" is considered a proof-of-principle test at the MLS by the SSMB collaboration.

An additional consequence of the beam in steady state is that the radiation from the beam is steady turn after turn. The radiated spot at the chips does not fluctuate, making it natural to meet the stability condition at the chips. SSMB is for IR, DUV, EUV, or THz radiation, all providing > 1 kW level of CW power per tool. There are several SSMB scenarios being proposed [2, 7, 8]. Different scenarios are to be used for different wavelengths of radiation aimed. For the EUV, the two leading scenarios are:

- 1. Strong focusing scheme
- 2. Reversible scheme

The strong focusing scheme requires a storage ring with very small momentum compaction $(low-\alpha_C)$ and small partial momentum compactions so that the microbunches do not smear out as the electron beam circulates around. A significant part of the accelerator physics effort aims to produce a lattice that fulfills this condition. In the reversible scheme, on the other hand, this requirement is not needed and the lattice does not require a low α_C . Instead, the two pairing modulators need to be designed so that their optical effects cancel each other accurately. Both of these schemes require design efforts and both are being pursued by the SSMB collaboration. We will make a selection when both designs mature.

Table 1 gives parameters of a few example conceptual SSMB designs. Three cases are given, IR, DUV and EUV. Strong focusing scheme has been used for all three wavelengths cases.

4 Design Efforts

Present efforts by the collaboration include the following:

- Tsinghua University Beijing: system integration, strong focusing lattice design, induction linac, injector, proof-of-principle test
- SSRF, Shanghai: SSMB scenarios, reversible lattice design
- NSRRC and NTHU, Hsin-Chu: laser system design
- SLAC: system integration, collective effects
- MLS, Berlin: proof-of-principle test
- Spring8: SSMB scenarios
- TSMC, Taiwan: laser system

4.1 Strong focusing lattice

The strong focusing lattice requires a small momentum compaction factor α_C . In addition, the partial momentum compactions around the ring must be kept small so as not to smear out the microbunches [9, 4]. A preliminary design layout is shown in Fig. 2 [10]. The circumference of this lattice is 94 m and the beam energy is 400 MeV. Nonlinear effects continue to be optimized together with simulation studies.

		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	А
$\Delta \delta_{\rm CSR}$	CSR pot. well distort.	2.5	2.3	2.4	10^{-3}
$ au_{\mathrm{RW}}$	resist. wall growth time	0.28	1.4	0.67	ms
$ au_{\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	$\mu \mathrm{m}$
$P_{\rm stored}$	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	$\mu \mathrm{m}$
B_r	bunching factor	0.29	0.29	0.29	
F	filling factor	38%	16%	93%	
P_r	SSMB rad.power/tool	4.2	1.4	1.12	kW

Table 1: Conceptual design parameters for three strong focusing example SSMBs for IR, DUV, EUV.

4.2 Reversible lattice

An alternative choice of a EUV SSMB lattice uses a reversible scheme in which the two modulators adopt the highly efficient transverse harmonic generation technique invented in [11], and the two chicanes are replaced by two dog-legs with the second dog-leg having a negative momentum compaction of $-R_{56}$ [12]. The modulation phase is also shifted by a phase of π . As a result, the second modulation optically undoes exactly the first one in each of the insertion section. The beam is microbunched inside the insertion but is without any microbunching in the rest of the storage ring. Smearing due to momentum compaction and partial momentum compaction is no longer an issue, and small α_C is no longer required. The price to pay is that the cancellation between the two modulation effects need to be accurately achieved, including any nonlinear effects. A preliminary reversible lattice design is shown in Fig. 3. Figure 3 also shows the simulation result. The energy spread increases by $\Delta \sigma_E / \sigma_E \sim 1.4 \times 10^{-4}$ per passage of this insertion, including the lattice nonlinearities. Field errors and



Figure 2: Layout of a preliminary SSMB storage ring lattice based on the strong focusing scheme.

collective effects are yet to be included.

4.3 Collective effects

Several collective effects have been taken into account in the parameters listed in Table 1, including the conventional impedance effects, intrabeam scattering, coherent synchrotron radiation, free electron laser instability, and the resistive wall instability. The beam intensities listed in Table 1 are taken to stay below these instabilities thresholds. The intrabeam scattering, for example, plays the main role demanding a sufficiently high beam energy. The coherent synchrotron radiation instability is the main effect determining the number of electrons per microbunch. For the EUV case, for example, there are only 4000 electrons per microbunch in the conceptual design given in Table 1. It should be noted that the CSR threshold is calculated assuming a 1-D thread beam, while the suppression of the instability due to a 2-D distribution of the SSMB beam has not been taken into account. The EUV power scales quadratically with the beam intensity per microbunch if this conservatism is not required. More detailed studies are continuing.

4.4 Nonlinear microbunch buckets

The seed laser needs to be strong to provide sufficiently high modulation voltage to the passing electrons. This is to maintain a longitudinal focusing to the electrons and to maintain a long quantum lifetime. The three cases in Table 1 are tracked for 1000 turns in the synchrotron phase space with their respective seed laser parameters. Figure 4 shows the results. To minimize the modulation



Figure 3: Layout and simulation of the preliminary insertion section for a reversible SSMB lattice.

nonlinearities, the wavelength of the seed laser λ_m is taken to be ~20 times the microbunch length σ_z . We require all cases in Fig. 4 to have at least a 6σ stability region to maintain sufficient quantum lifetimes of the microbunches.

We note that the condition of well-defined microbuckets is not a necessary condition for SSMB. Much shallower microbunching becomes a potential-well distortion instead of fully separated microbuckets, but still constitutes a fine SSMB mechanism, just with a reduced bunching factor.



Figure 4: Tracking results of microbucket longitudinal stability for the three cases of Table 1.

4.5 Seed laser

SSMB uses a high-power seed laser to modulate the electron energy at the modulators. The seed laser is envisioned to be a continuous-wave, IR laser stored between two high-reflectivity mirrors. The seed laser source does not require an extreme high power, depending on the achieved mirror reflectivity. The stored laser power within the laser cavity is assumed to be 1 MW, which is high but considered reachable using existing technology. The phase jitter of the stored laser is to be controlled to much below 0.1 fs. The jitter of the electron beam is envisioned to be slow enough that the electron microbunches will follow the strong focusing microbunch buckets.

The high power and the low jitter requirements are demanding. To fulfill these requirements, ultra narrow linewidth CW laser with optical cavity including feedback system is envisioned. The mirrors need more thinking if we choose ~ 200 nm laser as seed for EUV SSMB. The layout for the modulation laser system is shown in Fig. 5.



Figure 5: Layout for modulation laser system.

4.6 Induction Linac

Induction linac is preferred than traditional RF for energy supply to avoid the distortion on micro-structures and to obtain a long continuous train of microbunches. The required repetition rate of the induction linac is \sim a few MHz and the pulse voltage is \sim 10 kV. Multiple units can be used to reduce the requirement of the repetition rate for each.

5 SSMB proof-of-principle test

A proof-of-principle test is being proposed to be carried out at the MLS. In these tests, the seed laser is pulsed, and there is no laser cavity and no associated mirrors. In the first attempt, the beam is to be microbunched by a single shot seed laser pulse in an existing undulator in a nondispersive section. The laser is then turned off and the electron beam circulates around the ring. As it completes one turn, the same undulator now serves as the radiator. The radiation wavelength in this case is the same as the seed laser. The MLS lattice is to be set with a low $\alpha_C = 2 \times 10^{-5}$ and the beam energy is 250 MeV. The pulsed seed laser has wavelength of 800 nm, peak power of 0.5 MW, and a repetition rate of >1 kHz. The expected bunching factor of the electron beam after one turn is 0.25. Coherent radiation power from the beam on its second turn can exceed the original seed laser power if the electron beam intensity exceeds a peak current of 48 A, but otherwise anyway easily detectable, demonstrating the microbunching effect. Locking of the seed laser and the MLS RF system is expected to control the laser-beam timing jitter to < 0.5 ps.

In a second phase of the proof-of-principle test, we presently consider to propose a pulsed 10- μ m laser with 50-kW peak power and a repetition rate of 6.25 MHz. The purpose of this test is to demonstrate a "quasi-SSMB" in which the beam is not only microbunched but also a certain degree of steadystate is reached. The beam will not reach full steady state because, without a laser cavity, the seed laser power is not strong enough, and as a result, the microbunches are leaky. Furthermore, the MLS lattice controls α_C but not the partial momentum compactions around the ring, so the microbunches smear too quickly for a true steady-state to establish. We will measure the lifetime of the microbunches in the presence of the seed laser, and compare with our theoretical expectations.

The jitter tolerance of the laser-beam phase is < 1 fs. A laser frequency comb system based on f-2f interferometry is being considered to control phase jitter to this required level. It is expected that the electron beam jitter needs to be minimized for any frequency bandwidth beyond ~ 10 kHz, and this is an important condition to be verified by the test.

A simulation of quasi-SSMB is shown in Fig. 6. Most of the particles are lost by about 2×10^4 turns, but the remaining beam is sufficient to show an approach toward steady-state with established microbuckets after an initial single-pass transients. The electron beam has 300 MeV and the MLS storage ring has $\alpha_C = 2 \times 10^{-5}$ in this simulation.

If the proof-of-principle tests succeed, we intend to design and hopefully to build a full SSMB ring that aims for 1 kW at EUV.

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Figure 6: Expected evolution of the bunching factor in a quasi-SSMB experiment.

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