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STORAGE RING BASED STEADY STATE MICROBUNCHING

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Abstract

Powerful light sources are highly desired tools for scientific research and for industrial applications. Electrons are the objects that most readily and easily radiate photons. A natural conclusion follows that one should pursue electron accelerators as the choice tools towards powerful light sources. How to manipulate the electron beam in the accelerator so that it radiates light most efficiently, however, remains to be studied and its physical principle and technical limits be explored and optimized for the purpose. One such proposed concepts is based on the steady state microbunching (SSMB) mechanism in an electron storage ring. We make a brief introduction of the SSMB mechanism and its recent status in this presentation.

INTRODUCTION

As we have observed in the past few decades, modern physics has evolved out of the more traditional regime of nuclei and quarks, and now has backtracked to the regime of atoms and molecules. This means the prime research means has evolved out of particles of ever higher energies and into photons of various wavelengths, and the tools have evolved out of colliders and into light sources. This trend has been a major evolution expected to continue in the next decades.

At presnt, there are two main approaches in advanced light sources, the third- (and fourth-) generation storage ring synchotron radiation sources, and free electron lasers.

In a third-generation synchrotron radiation light source, with an RF focusing, the electron bunches are separated by perhaps ∼1 m, while each bunch has a length of the order of ∼10 mm. With the electrons circulating around the storage ring in steady state, the radiation has a high repetition rate. However, with a bunch much longer than the wavelength of radiation, the radiation from the electrons is incoherent. The radiation peak power is low, proportional to N, the number of electrons in the bunch.

In a free electron laser light source, on the other hand, the electrons are provided by a linac. A single electron bunch is cleverly manipulated in such a way that it gets microbunched by the time it is about to exit a long undulator and therefore radiates coherently, with a very high peak power proportional to N^2. However, using a linac in a pulsed mode, the repetition rate is low.

The present situation is therefore that, towards the goal of high power light sources, one of our main approaches has a high repetition rate but low peak power, the other has a high peak power but low repetition rate. Since the net radiation power is the product of repetition rate and peak power, we naturally come to an idea of a somehow combined device. This device aims to have both the high repetition rate of a storage ring and a high peak power of a microbunched beam like in an FEL.

It must be quickly pointed out that a straigtforward insertion of a long undulator in a storage ring will destroy the microbunches of the electron beam — FELs always use linacs for a good reason. If an FEL linac is simply inserted into a storage ring, the storage ring will have to be operated in a pulsed mode; every time the electron beam traverses the FEL, it has to wait in the storage ring for a long time to cool down before a next passage can be made, effectively making this device a pulsed operation and the benefit of high repetion rate of the storage ring does not apply.

Such a combined device must be done while keeping the intigrity of the microbunched structure of the electron beam. The way being proposed to accomplish this is named steady state microbunching (SSMB). Once accomplished, an SSMB device aims for simultaneously a high repetition rate and a high peak power. Since N is a very large number, an SSMB ring potentially gains a large factor in the desired radiation power compared to a third-generation storage ring facility.

In terms of its operation principle, this conceived storage ring-based SSMB functions very closely to that of a conventional storage ring, except that the microwave RF is replaced by an IR laser modulator. The equilibrium beam distribution becomes microbunched with the bunch spacing given by the modulation laser wavelength λ_m instead of a conventional RF wavelength. This represents an extrapolation of six orders of magnitude in bunch spacing but the mechanism of the steady state is the same, i.e., a balance between radiation damping and quantum excitation. No FEL mechanism is invoked. To demonstrate the applicability of our resent understanding of storage rings to this six orders of magnitude extrapolation, a critical proof-of-principle test has been launched.

SSMB SCENARIOS

Before we discuss its technical design, we first need to know that there are a variety of SSMBs that one can aim for, ranging from simple to sophisticated ones. Depending on the applications, particularly depending on the targeted wavelength of the SSMB radiation, there are several different SSMB scenarios with different levels of sophistication.

To illustrate the various scenarios, we start with a conventional third-generation storage ring source. The electron beam is bunched with a Gaussian distribution with bunch length ∼10 mm. The radiation is incoherent, as mentioned. If the targeted wavelegnth is long enough, e.g., in the THz range, then by some conventional techniques, one may try to compress the bunch length toward the desired wavelength and accomplish some enhancement of the radiation. This source however remains basically a conventional design.

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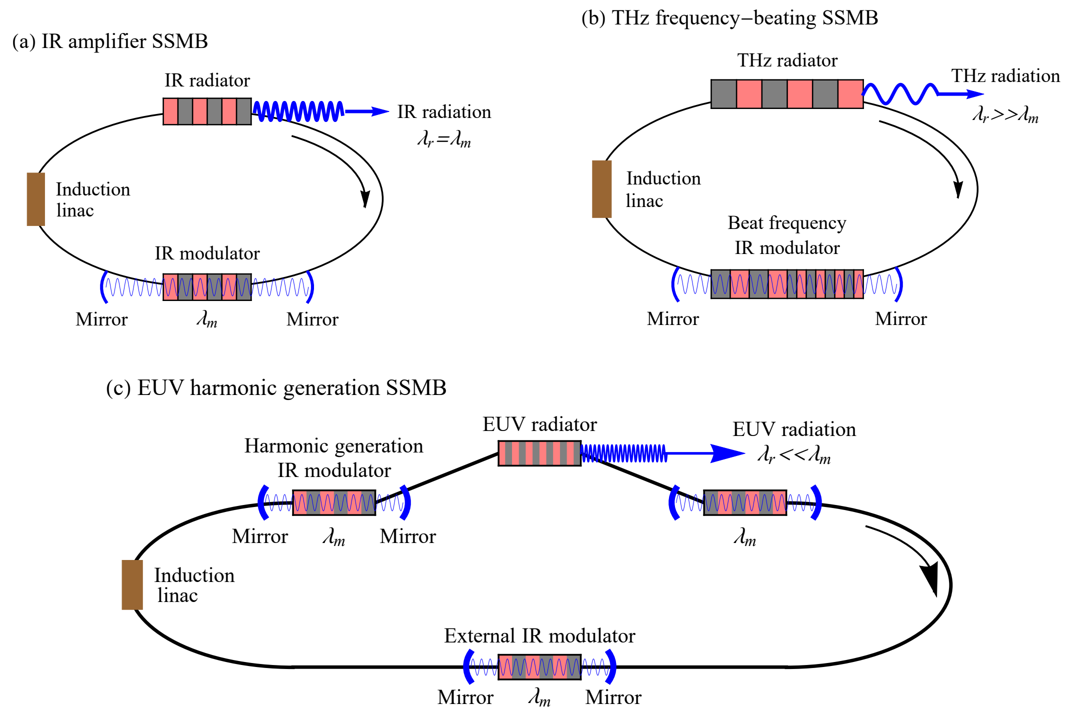

Figure 1: SSMB scenarios for different radiation wavelengths. (a) $\lambda_r = \lambda_m$; (b) $\lambda_r \gg \lambda_m$; (c) $\lambda_r \ll \lambda_m$.

Potential-well Distortion SSMB

The very simplest SSMB scenario is to start with the conventional beam and slightly modulate its equilibrium Gaussian distribution to generate a small micro-structure on top of the Gaussian. This can be accomplished by adding a laser modulator in the storage ring so that a weak laser modulation is superimposed onto the large RF waveform. The traditional quadratic potential well provided by the RF system is then ever so slightly potential-well distorted by the laser modulation. The laser wavelength is an exact k times shorter than the RF wavelength, where k is a large integer. Once modulated, this slightly micro-modulated beam will circulate around the storage ring in a steady state and will radiate coherently at the desired wavelength. Although the modulation is only very slight, its coherent radiation easily overwhelms the conventional synchrotron radiation because of the extra factor of N. This scenario is the simplest SSMB scenario and is not expectd to be difficult to implement as it requires basically only a stable conventional storage ring.

As a numerical example, consider an electron beam in a typical conventional electron storage ring. Let this beam have an average current of $I_{ave} = 0.5$ A and let its natural Gaussian bunch have a peak current $I_{peak} = 50$ A. Now let this beam be slightly modulated at 1 μm wavelength by a moderate IR modulator, so that it has a bunching factor $\mathcal{B} = 0.01$ at 1 μm. Now assume an undulator radiator with $K = 2$ and total number of radiator periods $N_u = 40$. This SSMB source will radiate at 1 μm wavelength a power of 25 W (peak power 2.5 kW),

$$P_{ave} = \frac{\pi}{\epsilon_0 c}|\mathcal{B}|^2 \xi [JJ]^2 N_u I_{ave} I_{peak}, \tag{1}$$

where $[JJ] = J_0(\xi) - J_1(\xi)$, with $\xi = K^2/(4+2K^2)$.

This numerical example indicates that a slightly modulated simplest SSMB is already a respectable radiator. This SSMB ring does not require any demanding momentum compaction factor and can be applied to existing conventional electron rings.

Amplifier SSMB

To increase the SSMB radiation power of a slightly potential-well modulated SSMB, naturally we want to increase the laser modulation strength. We then consider a case when the beam is fully modulated [$\mathcal{B} \to 1$ in Eq. (1)]. This beam radiates coherently at the modulation wavelength. The SSMB then serves as a very strong amplifier of the original modulation laser.

One weakness of this amplifier SSMB is that, to apply this SSMB at a certain desired wavelength, one needs to have already an existing laser of the same wavelength to be used as the modulation laser. This SSMB only amplifies the exisiting laser, although the amplification factor can be very large.

The SSMB research so far has included an important proof of principle test. This test is being carried out at the Metrology Light Source MLS, Berlin. Its phase I has been quite successful [1], and its phase II is being initiated. A successful proof of principle test is in fact already a realization of an amplifier SSMB. We will discuss more of this test experiment later in this presentation.

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Harmonic Generation SSMB

A practical existing laser could be an IR laser. It is natural to consider an IR laser as the modulation laser for the SSMB scenarios. As such, the potential-well-distortion and the amplifier scenarios are readily available for IR radiation, and for them, there is not much additional accelerator technology needed beyond existing state-of-the-art. What requires additional R&D is when we consider a scenario when the desired radiation has a wavelength much shorter than IR. For those applications, there is an additional step of harmonic generation required. We refer to this scenario the harmonic generation SSMB.

One reason of a need to consider harmonic generation, in spite of the additional R&D needed, is its potential to some special industrial applications. In particular, we need to consider it if the wavelength we desire is DUV, EUV, or soft Xray. We will say more about the on-going efforts in the R&D and design of a harmonic generation SSMB later in this presentation.

THz SSMB

Considering an IR modulation laser, harmonic generation provides a way to shorten the radiation wavelength. An SSMB scenario also provides a way to lengthen the radiation wavelength to, e.g., the THz range [2]. This can be done by taking an amplifier SSMB, and simply replacing the modulator undulator by two back-to-back shorter undulators. The two undulators have slightly different resonant frequencies, with both of their resonance bandwidths covering the modulation laser, but slightly differ by a frequency split of 1 THz. The electron beam distribution then contains a strong beat frequency component at 1 THz, thus producing SSMB radiation at 1 THz.

FEL-ERL Based Scenario [3]

We have so far emphasized the role of a storage ring, and it was noted that a ring-based SSMB is not an FEL. FEL linacs are of course quite capable of producing radiation at desired wavelengths. To make them powerful light sources, however, it becomes necessary to increase substantially the linac repetition rate by adopting a superconducting gun and linac, and to add an energy recovery linac to recover the electron beam energy. Such a concept is not included in the ring-based SSMB discussed here. On the other hand, the two concepts are not too dissimilar. In the FEL-ERL scenario, the steady state is maintained not by reusing the electron beam but by reusing the electron beam energy. Other than how the steady state is maintained, the principle of SSMB and particularly the microbunching beam dynamics, including its harmonic generation, are quite similar.

Figure 1 intends to illustrate more design details of three of the SSMB scenarios. Figure 1(a) shows an amplifier version. The modulation laser is stored in a laser cavity. The radiated laser has the same wavelength (assumed to be IR) but is amplified by a large factor. Beam energy is replenished not by a conventional RF but by an induction linac [4]. Figure 1(b) shows the conceptual design of a THz SSMB. The modulator undulator now has a design with dual resonant frequencies that split by THz. In this case, the radiation wavelength is much longer than IR. Figure 1(c) is a harmonic generation SSMB, aiming for radiating a much shorter wavelength than IR, e.g., in the EUV regime. In this case, a much more complex radiator section replaces the simple radiator undulator. On each side of the radiator, a harmonic generation modulator is installed to further compress the microbunch. The two modulators sandwiching the radiator are made to compensate each other, so that the electron beam is restored before reentering the ring arcs.

PROOF OF PRINCIPLE TEST

To test the SSMB mechanism, a proof of principle experiment is carried out at the MLS, Berlin [1, 5–7]. Figure 2 illustrates the conceived three phases in the SSMB planning. Phases I and II are proof-of-principle tests. Phase III is the design and construction of a dedicated SSMB storage ring.

Phase I, a critical proof-of-principle step, has been demonstrated [1]. A single-shot laser is used to establish the feasibility in a low momentum-compaction environment that is suitable for sustaining the microbunched beams for multiple turns. In the experiment, after the beam is stably stored in the ring, a single-shot IR laser pulse is fired to excite the beam with energy modulation. A precision semi-isochronous storage ring optics causes the beam to microbunch at its next turn. The modulating undulator then serves as the radiator in the subsequent turns of the beam. An SSMB effect is detected by the coherent radiation of the microbunched beam for multiple turns following the single-shot of the laser.

In this single-shot experiment, the fundamental 1064-nm SSMB signal is interfered from the original modulation laser, so the experiment was carried out by detecting the second

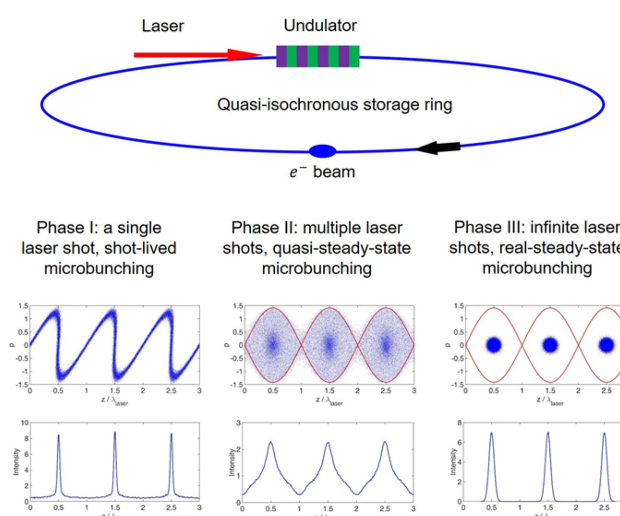

Figure 2: Conceived three SSMB phases. Phases I and II are proof-of-principle tests. Phase I has been demonstrated. Phase II is currently restarted since COVID. Phase III, presently under a design effort, is the eventual construction of a dedicated harmonic generation SSMB ring.

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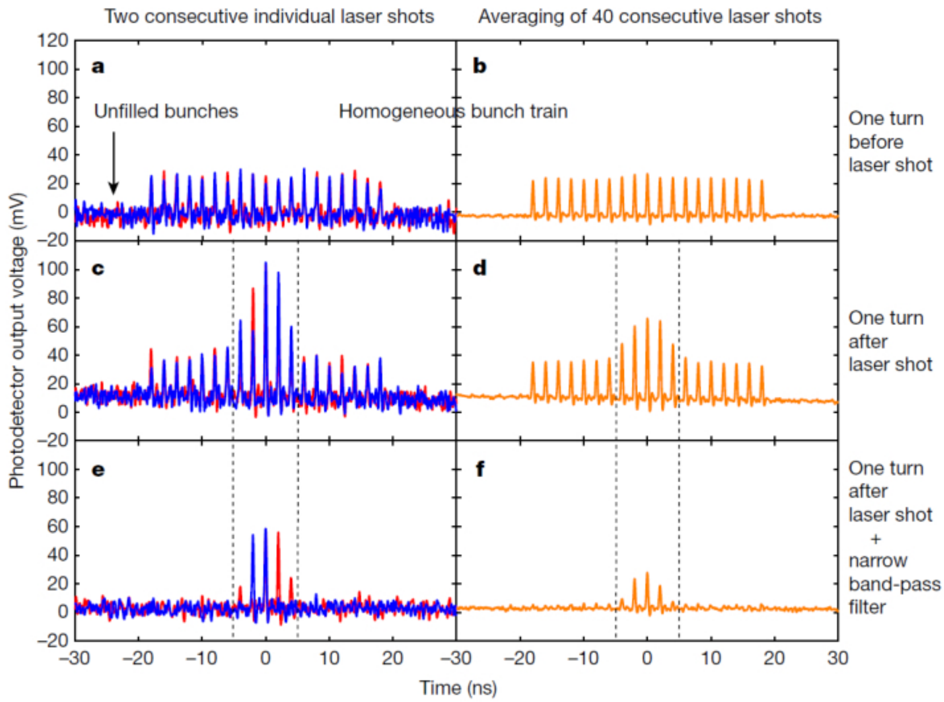

Figure 3: Coherent SSMB radiation demonstration in phase I proof of principle test at MLS.

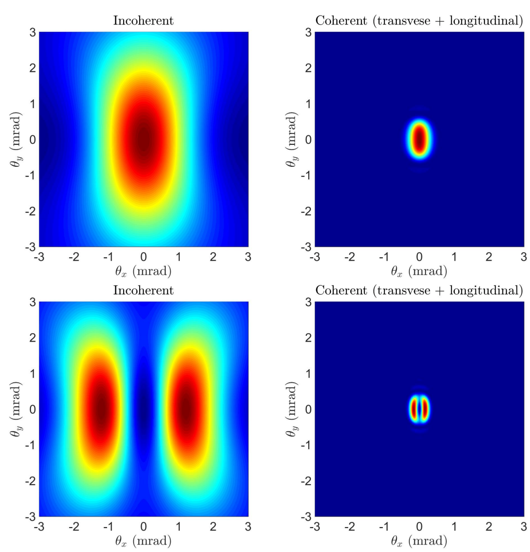

Figure 4: Angular distribution patterns of the expected SSMB radiation from the proof of principle test. The left column shows the patterns for the incoherent undulator radiation (upper figure for the fundamental 1064 nm mode, lower figure for the 532 nm second-harmonic mode). The right column shows the same for the coherent SSMB radiation. All plots have the same scales of axes.

harmonic 532-nm radiation. Robust signals were detected. One set of data is shown in Fig. 3. Before the laser shot, a 19-bunch beam is stored in the ring. Figure 3(a) shows 19 incoherent synchrotron radiation peaks. A laser shot is then fired, affecting 5 in the middle of the 19 bunches. On the next turn of the beam, these 5 bunches get microbunched. Figure 3(c) shows their enhanced radiation. When a frequency filter is installed in front of the detector, filtering out the wide-spectrum of the incoherent radiation, Fig. 3(e) shows that only the coherent SSMB signal from the middle bunches remains, proving the enhanced radiation is truly from the microbunching mechanism. Figures 3(a), (c), (e) show the measurements of two laser shots. Figures 3(b), (d), (f) repeat (a), (c), (e) with the signals averaged over 40 consecutive shots.

In addition to the narrower frequency range, the coherent radiation is expected also to have a narrower angular spread. Figure 4 shows the expected angular pattern of the radiation in the PoP test [8]. The coherent radiation is expected to be much more collimated than the incoherent radiation. Investigation of these interesting features are being continued.

After the laser shot, the beam is microbunched and radiate coherently in its next turn. This microbunched beam can be rather robust. Its microbunching structure can last for several revolutions without additional laser shots [7]. A case with robust microbunched beam is shown in Fig. 5.

This multi-turn result is very encouraging. After a single shot of the laser, the microbunched beam is robust over several revolutions. If we continue to fire the laser, it is expected that the beam will stay microbunched circulating around the ring. This is what the phase-II experiment aims to demonstrate. The single-shot laser is to be replaced by a high repetition laser. In the phase-II experiment, the microbunches are expected to slowly leak out of the microbuckets. Its SSMB state is therefore a quasi-steady-state, as indicated in Fig. 2(b). A fully steady SSMB awaits a dedicated storage ring, currently under a design effort.

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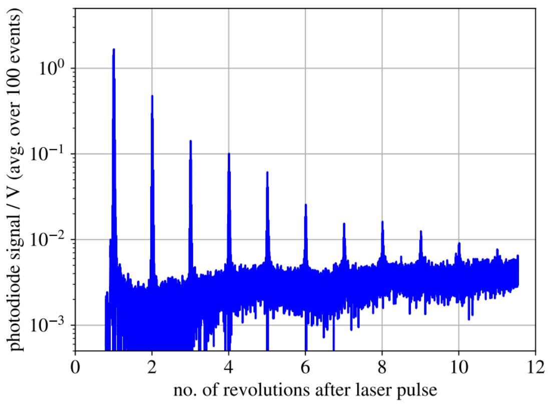

Figure 5: SSMB proof of principle signal lasts for multiple turns.

HARMONIC GENERATION SSMB DESIGN EFFORT

As mentioned, for applications to radiation wavelengths in the DUV, EUV and soft Xray ranges, an additional step of harmonic generation is needed. To this end, a team was organized at Tsinghua University, Beijing to investigate the technical issues involved and to make a first proposal of such a dedicated device [5, 9]. The effort is continuing and preliminary designs, one aiming DUV and one aiming EUV, are in progress.

Various ways to perform the harmonic generating microbunch compression have been investigated [4, 10]. In the present design concept, two laser modulators are inserted on each side of the DUV/EUV radiator to provide an additional step of bunch compression at the radiator in the middle, as sketched in Fig. 1(c). The two modulators impose equal and opposite modulations in a reversible configuration [11, 12]. To minimize the required modulation laser power, a clever idea based on an angular dispersive modulation and longitudinal-transverse coupling mechanism [3, 13] is implemented.

The SSMB design focuses on longitudinal beam dynamics, particularly the implementation of strong focusing in the longitudinal dimension not unlike the transverse final focusing in a collider. In particular, the concept of strong focusing is further extended from 2D beam dynamics to 6D [13]. In contrast, a fouth-generation synchrotron radiation source concentrates on its transverse beam dynamics.

Various accelerator physics issues need to be addressed, including a storage ring lattice that permits a steady-state microbunched beam configuration including an insertion of harmonic generation [14, 15], in-depth understanding of various 6D single-particle dynamics [16], and various collective effects [4, 17, 18].

Other critical areas in the SSMB design effort include its laser and modulator section, and the demanding laser optical cavity [19]. A sketch if shown in Fig. 6.

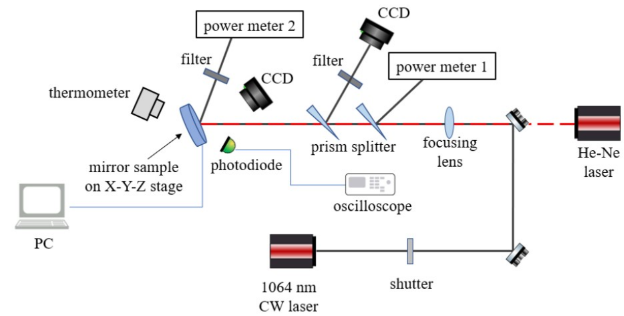

Figure 6: Present design layout of a SSMB laser system.

Figure 7: The high performance linac has included a wakefield compensation mechanism.

Another important technical requirement is a high performance injector, with demand of a wakefield compensated linac, sketched in Fig. 7, and a stretcher ring [20].

The design parameters vary according to the targeted radiation wavelength. The parameters evolve as the design efforts deepen. For a snapshot of the design status, Table 1 gives one recent version of parameters of two dedicated SSMB storage rings, one DUV and one EUV. More design examples aimed at other wavelengths, as well as a comprehensive set of design equations, are presented in [21]. An EUV SSMB layout is sketched in Fig. 8.

In the approach adopted in establishing Table 1, with the additional bunch compression done mostly in the reversible radiation section, the requirement on a short microbunch length in the storage ring is lifted. This also lifts the demand on an extra small momentum compaction factor α_c. The storage ring lattice is very much relaxed, while the burden of harmonic generation is taken up by the radiator insertion section. Another important implication of this design is that

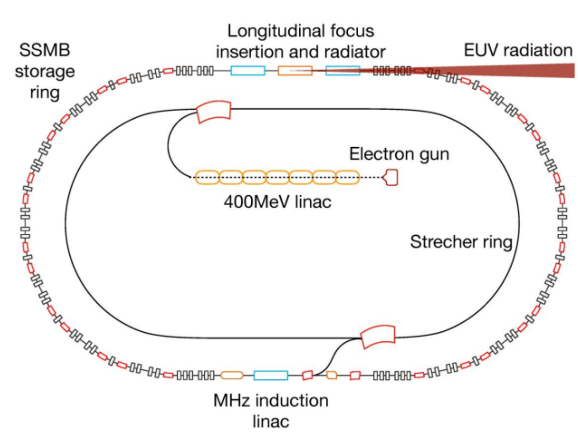

Figure 8: SSMB EUV design layout as of today.

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Table 1: A sample list of parameters for a DUV and an EUV SSMB facility. Both examples require harmonic generation.

Parameter	**SSMB-DUV**	**SSMB-EUV**	**Unit**
C_0, circumference	100	100	m
E_0, beam energy	320	800	MeV
I_0, beam current	1	1	A
τ_δ, longitudinal damping time	92	14.7	ms
$\sigma_{\delta 0}$, energy spread	3.1	$4.85 \cdot 10^{-4}$	
σ_z(rad), bunch length at Radiator	10	2	nm
ϵ_y, vertical emittance	20	2	pm
λ_{mod}, modulation laser wavelength	1064	270	nm
h, modulation chirp slope	1000	541	m^{-1}
L_u(mod), modulator length	1.8	1.5	m
P_{mod}, modulation laser power	326	141	kW
n, harmonic number	10	20	
λ_{rad}, radiation wavelength	106.4	13.5	nm
L_u(rad), radiator length	3	3.2	m
$\mathcal{B}$, bunching factor	0.174	0.11	
$P_{\mathrm{rad,cw}}$, radiation power in c.w. mode	1	1	kW

intrabeam scattering and the coherent synchrotron radiation effects are also more relaxed.

SUMMARY

1. Proof of principle Phase I experiment successfully demonstrated the feasibility of the SSMB approach. Phase II experiment is being reinitiated at MLS after a 3-year COVID pause.

2. There are several scenarios of the SSMB light sources.
   - An amplifier scenario uses a conventional storage ring, readily available as a powerful IR source.
   - THz scenario requires a conventional storage ring plus a dual undulator.
   - Harmonic generation SSMB is in active R&D. Design parameters are being formulated and forthcoming.

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