EXPLORING THE NECESSARY CONDITIONS FOR STEADY-STATE MICROBUNCHING AT THE METROLOGY LIGHT SOURCE

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Abstract

Steady-state microbunching (SSMB) has been proposed as a new mechanism to generate coherent synchrotron radiation at a storage ring facility with short wavelengths up to the EUV range. This promises a narrow band, high average power radiation source. A proof-of-principle (PoP) experiment at the Metrology Light Source (MLS) has shown the viability of the underlying mechanism, and now the necessary storage ring conditions for the generation of microbunching are investigated. In this paper, a summary of some key theoretical aspects is given and the setup of the PoP experiment is summarized. We present recent results from the experimental investigations, which include the survival of microbunching for several revolutions. We highlight the importance of considering nonlinear momentum compaction effects as coherent radiation is so far only observed in an alpha bucket state.

INTRODUCTION

Currently, two kinds of synchrotron light sources are dominant: Free electron lasers supply high peak power coherent light but can provide only low repetition rate, as they are based on linear accelerators. Electron storage rings offer high repetition rates but the generated radiation is generally incoherent.

Steady-state microbunching (SSMB) is proposed [1, 2] to combine the properties of FELs and storage rings, by invoking a scaling of the longitudinal focusing mechanism over several orders of magnitude, from radio frequency (RF) to optical wavelengths. In this way, the bunch spacing and bunch length is reduced while maintaining a stable, steady-state storage of these microbunches, allowing the wavelength range for which the production of coherent synchrotron radiation is possible to be extended into the extreme ultraviolet (EUV). The EUV range is of particular interest because of its possible application in computer chip manufacturing [3].

To realize SSMB, a dedicated accelerator facility needs to be designed [4–6]. The most commonly proposed concept envisions the RF cavity to be replaced in its functions separately: by an optical laser modulator to create the microbunch structure and by an induction linac [7] to resupply the synchrotron radiation losses.

As a first step, a proof-of-principle (PoP) experiment is needed to verify the concept and explore the necessary parameters for a future SSMB facility.

THEORETICAL ASPECTS

Requirements for SSMB

There are a number of requirements on storage ring parameters to allow the formation of microbunches [8, 9]. Most fundamentally, the lattice needs to be quasi-isochronous to sustain these ultrashort structures. This requires a low momentum compaction of $\alpha_0 < 2 \times 10^{-5}$. In this regime one also has to consider local phase slippage and longitudinal diffusion brought about by the stochasticity of the emission of synchrotron radiation, increasing bunch length and energy spread [10, 11].

Furthermore, transverse-longitudinal coupling must be suppressed, most crucially from the horizontal to the longitudinal plane, so that betatron oscillations do not destroy the longitudinal phase correlation. For this, the horizontal chromatic function

$$H_x = \gamma_x D_x^2 + 2\alpha_x D_x D_x' + \beta_x D_x'^2 \tag{1}$$

must be nearly zero at the undulator (α_x, β_x, γ_x are the Courant-Snyder functions in the horizontal plane). Thus we require horizontal dispersion D_x and dispersion angle D_x' be at the level of few mm and 0.1 mrad at the undulator, respectively. Also, the horizontal chromaticity $|\xi_x|$ should be low to reduce path length changes from betatron oscillations, but not too low as to avoid collective instabilities. In the experiment, $\xi_x = -0.5$ is chosen.

Nonlinear Momentum Compaction and Alpha Buckets

When the momentum compaction factor α becomes very small, it can no longer be considered constant, but its dependence on the particle energy becomes important [12]. Considering the relative momentum deviation $\delta = (p - p_0)\,/p_0$,

$$\alpha = \alpha(\delta) = \alpha_0 + \alpha_1\delta + \alpha_2\delta^2 + ... \tag{2}$$

and the roots of this function give rise to additional fixed points in longitudinal phase space. An example is plotted in Fig. 1, showing a phase space similar to the situation in the SSMB PoP experiment. The leading order α_0 can be manipulated by changing quadrupole strengths, and when changing the sign of α_0, instead of the beam being lost, the conventional RF bucket transforms into one or more alpha buckets. The bucket shapes are determined by the higher orders of the momentum compaction, which can be manipulated via higher order multipole magnets.

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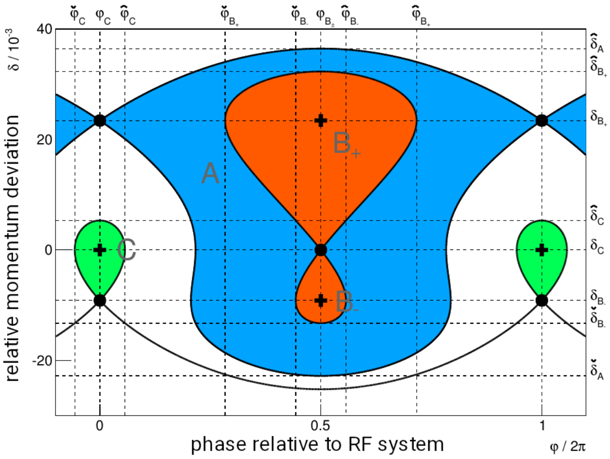

Figure 1: Longitudinal phase space considering nonlinear momentum compaction with $\alpha_1 < 0$, $\alpha_2 > 0$. Alpha buckets (B_+, B_-) and RF bucket (C) are present at different phase and energies. The stable region A allows for charge transfer between the B_+ and B_- buckets.

EXPERIMENTAL INVESTIGATIONS

The Metrology Light Source

The Metrology Light Source (MLS) is an electron storage ring owned by PTB and operated by HZB in Berlin, Germany [13, 14]. It has been designed and optimized for low alpha operation, with dedicated sextupole and octupole magnet families to control the higher order momentum compaction, and as such is uniquely suited for the SSMB proof-of-principle experiment presented here. Table 1 lists important storage ring parameters of the MLS for standard operation and the SSMB experiment.

Table 1: Machine Parameters of the MLS Storage Ring for Standard Operation and the SSMB PoP Experiment

Parameter	**Standard Op.**	**SSMB PoP**
Circumference C_0	48 m	48 m
Beam energy E_0	629 MeV	250 MeV
Bunch charge Q_b	400 pC	< 10 pC
Momentum comp. α_0	0.03	$< 2 \times 10^{-5}$

The SSMB Proof-of-Principle Experiment

The setup for the SSMB PoP experiment at the MLS employs the same undulator for modulation with a laser pulse and for radiation (see Fig. 2). The whole storage ring optics are used to transform the energy modulation into physical microbunching, this is achieved by applying quasi-isochronous optics while controlling a number of parameters, as explained above. In the current, first phase of the SSMB PoP experiment, a single shot modulation by a laser within the MLS undulator is employed. The undulator radiation is monitored in the revolutions following the modulation on the first and second undulator harmonics. First harmonic detection is non-trivial, as the strong modulation laser pulse is also present in the detection path at the same wavelength [15, 16].

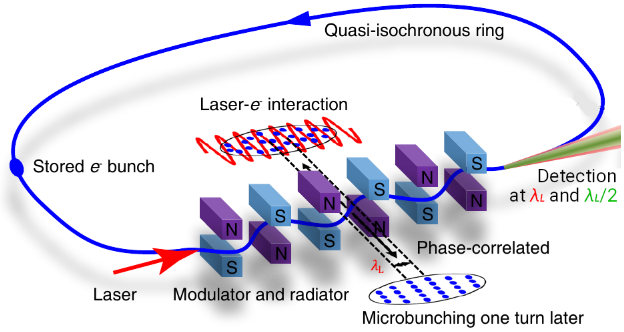

Figure 2: Schematic setup for the SSMB PoP experiment at the MLS.

Results

Coherent undulator radiation from microbunching has been first observed in 2019 [8]. Since then, improvements to the experimental setup [15, 16] have allowed systematic studies to evaluate the conditions necessary to obtain microbunching.

From the experimental evidence it is clear that nonlinear momentum compaction plays a crucial role in the generation of microbunching. In fact, so far coherent emission has only been observed in a specific alpha bucket state, of the B_- type as shown in Fig. 1. Simulation studies to reproduce this behavior as well as experimental searches for microbunching in other states are ongoing.

Quadratic current scaling The coherent nature of the observed radiation has been proven repeatedly by observing a quadratic dependence of the radiation power to the bunch charge, as seen in Fig. 3. There is a significant, reproducible horizontal offset to the quadratic fit. This may be explained by residual charge stored in a different bucket, which only radiates incoherently, as multiple alpha buckets are populated simultaneously. Above a bunch charge of $Q_b \approx 2.5$ pC, a saturation-like behavior sets in, as collective instabilities begin to disturb the microbunching process.

Dependence on RF Cavity Voltage Experimental investigations have shown a counter-intuitive and complex dependence of the emitted coherent radiation power on the RF cavity voltage. Figure 4 shows this dependence and its evolution with decaying bunch charge. For the high current case, high cavity voltages are favored, as might be expected due to the higher charge density. However, for low bunch charge, lower cavity voltages now give a stronger coherent emission. Additionally, there is a distinct voltage threshold above which the coherent signal breaks down significantly, in the case shown in Fig. 4 at $U_{cav} \approx 350$ kV. The drop around 150 kV is caused by the synchrotron tune crossing an

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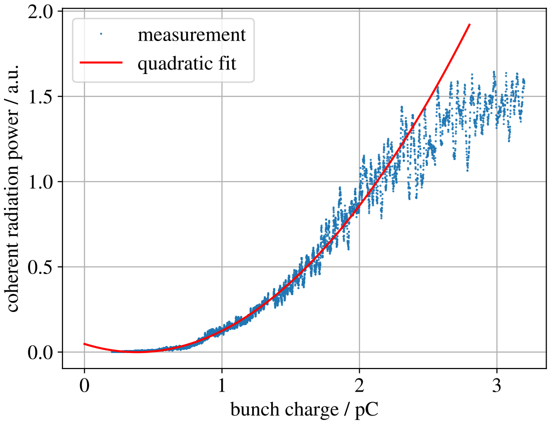

Figure 3: Quadratic scaling of the undulator radiation in the SSMB PoP experiment, proving its coherent nature.

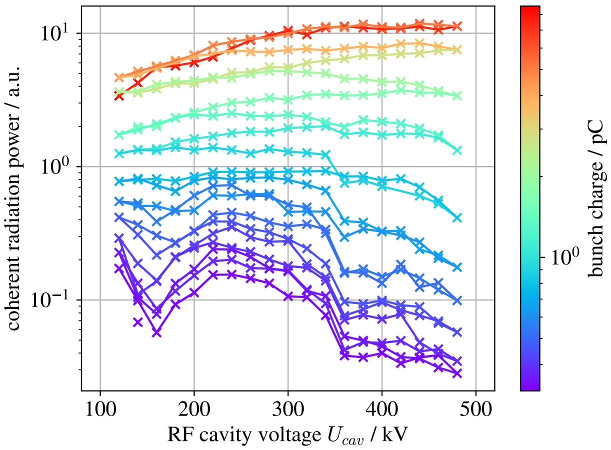

Figure 4: Dependence of the coherent signal on RF cavity voltage recorded during a single experiment with decaying beam current. For low bunch charge, lower cavity voltages are favored.

excitation line in the RF spectrum. The behavior at 350 kV is currently not understood and is a focus of study.

Multi-turn coherent emission Even though in the current stage of the PoP experiment laser modulation is only performed as a single shot, microbunching created in the following revolution around the storage ring can survive for additional turns around the machine. This verifies that the electron longitudinal coordinate can be correlated turn-by-turn at a precision below the laser wavelength which is crucial for the future realization of SSMB.

Figure 5 shows an example where enhanced emission is observed up to the 11th revolution after modulation. The emitted radiation power roughly exhibits an exponential decay with additional turns. This high number of revolutions still exhibiting coherent emission—in some cases coherent radiation has been observed after more than 30 turns—is unexpected. It is an indication that the microbunching generated from a single-shot modulation is already more robust than expected.

The behavior of the higher revolution coherent emission is complex, for example there are storage ring settings where first revolution emission is suppressed, but there is a clear signal on the fourth and fifth revolutions after modulation. This is the case when the required parameters as explained above are slightly detuned from their optimal values. This effect is not yet understood, but it may be tied to some residual transverse-longitudinal coupling, as the fractional vertical tune during the experiment is $q_y = 0.23$.

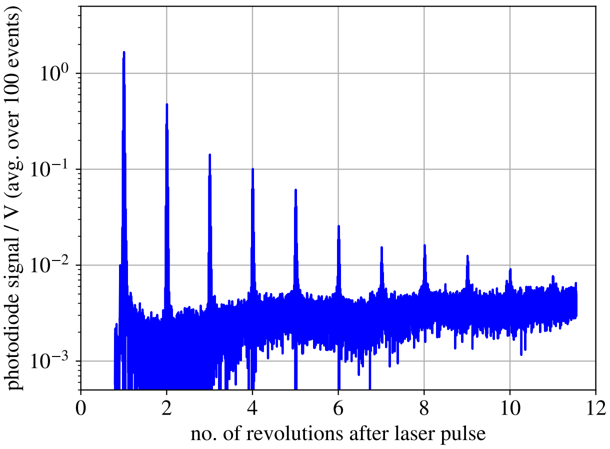

Figure 5: Coherent undulator radiation is emitted for more than the first revolution after modulation.

CONCLUSION

The successful results from the first phase of the SSMB PoP experiment have been presented. Unexpected experimental results about the storage ring conditions necessary for the generation of microbunching require further experimental investigations as well as simulation studies to understand the experimental results. Such studies, especially about the importance of nonlinear momentum compaction and alpha buckets, are ongoing. The next phase of the SSMB PoP project at the MLS is currently planned, with a high repetition rate phase-locked laser to modulate the electron beam turn-by-turn to achieve a quasi-steady state.

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