QUASI-STEADY-STATE MICROBUNCHING FROM MULTI-TURN LASER MODULATION AT THE METROLOGY LIGHT SOURCE

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Abstract

Steady-state microbunching (SSMB) has been proposed as a scheme to generate high average power coherent synchrotron radiation at short wavelengths from an electron storage ring. To evaluate the feasibility of this scheme, a proof-of-principle experiment is conducted at the Metrology Light Source (MLS) in Berlin, the first phase of which (PoP I) was concluded in 2024. PoP I utilized a single-shot laser system to provide an energy modulation to the electron beam and investigated the fundamental requirements on storage ring dynamics to enable SSMB. Recently, the second phase of the SSMB proof-of-principle experiment (PoP II) has commenced at the MLS, in which a high repetition rate phase-locked laser system provides turn-by-turn energy modulation of the electron beam on consecutive revolutions around the storage ring. The main goal of SSMB PoP II is to show electrons can be confined to individual microbuckets defined by this laser interaction, reaching a quasi-steady state. This paper presents the first results obtained in SSMB PoP II, where coherent synchrotron radiation has been detected following multi-turn laser modulation, and the ongoing systematic studies of the underlying microbunching process.

INTRODUCTION

To fulfil demands for high average power ultraviolet light sources, for applications such as EUV lithography, the idea of steady-state microbunching (SSMB) has been proposed [1, 2]. The goal of SSMB is to continuously store a microbunched electron beam in a storage ring to enable production of coherent short-wavelength radiation while also benefiting from the inherent high repetition rate of a storage ring to yield very high average power radiation. Theoretical design studies for a possible future SSMB storage ring are ongoing [3–7] and a proof-of-principle (PoP) experiment at the Metrology Light Source (MLS) in Berlin is exploring the feasibility of the idea.

Previously, the SSMB PoP experiment utilized a single-shot laser system to imprint a singular energy modulation onto the electron beam. This phase I of the experiment was successful in showing that the full circumference of the MLS storage ring could be used as a dispersive section to create a microbunching structure from this modulation [8, 9], and explored the necessary conditions on the storage ring optics [10, 11]. Since 2025, phase II of the SSMB PoP experiment has commenced at the MLS and aims to reach microbunching in a quasi-steady state by employing turn-by-turn energy modulation of the electron beam for up to 1000 consecutive revolutions around the storage ring, utilizing a high repetition rate phase-locked laser system [12, 13]. The key goal of SSMB PoP phase II will be to show that electrons can be confined to microbuckets defined by the laser field and perform synchrotron oscillations within.

EXPERIMENTAL SETUP

For phase II of the SSMB PoP experiments, the setup is mostly retained from the phase I efforts, most notably the radiation detection setup at the beamline [14], which remains unchanged except for changes to the triggering procedure [15]. Figure 1 shows a basic sketch of the setup: Energy modulation of the electron beam is achieved by co-propagating a laser in an undulator, the beam is microbunched by transport through the suitably tuned quasi-isochronous storage ring optics, and the coherent radiation emitted at the same undulator and at the same wavelength as the modulation laser is detected on following revolutions. For phase II, a high repetition rate laser system for turn-by-turn modulation is available [12, 13], some key parameters are compared to the previous laser system in Table 1.

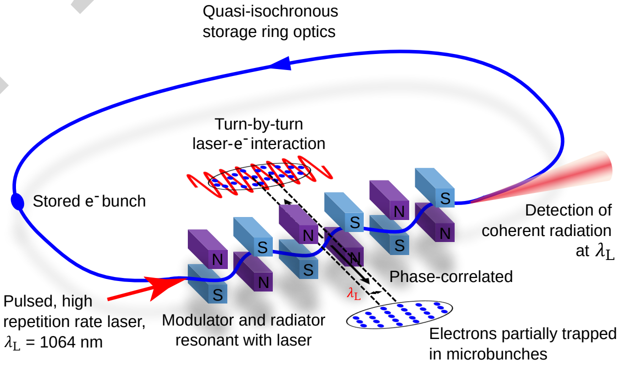

Figure 1: Schematic setup of the SSMB proof-of-principle experiment.

Both laser systems are still available for use with minimum switching effort [15], which is very useful for the setup of the storage ring optics. Because the maximum peak power of the phase II laser is a factor of 1000 weaker than the phase I laser, resulting in an energy modulation depth reduced by a factor of 30, it is significantly more challenging to achieve a reasonable bunching factor in order to be able

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Table 1: Laser Properties for SSMB Proof-of-Principle Experiment Phase I and II

Parameter	Phase I laser	Phase II laser
wavelength	1064 nm	1064 nm
pulse length	5 ns FWHM	700 ps flat-top
peak power	20 MW	20 kW
repetition rate	1.25 Hz	6.25 MHz

to detect coherent undulator radiation of sufficient magnitude for systematic studies. Thus, the phase I laser is used to first optimize the conditions for microbunching before switching to the phase II laser. Preparation of storage ring parameters include optimizing the phase slippage factor and its first two nonlinear orders, minimizing dispersion and dispersion angle at the undulator as well as measurement and optimization of transverse and longitudinal chromaticities to near zero values. Optimal transverse as well as longitudinal overlap between laser and electron bunch is also crucial for PoP phase II, and is checked before each measurement campaign.

SIMULATION

For the work presented in this paper, we are mainly interested in the onset of microbunching on the first few revolutions as turn-by-turn modulation commences from an equilibrium. Figure 2 shows the coherent radiation power simulated for different values of the linear phase slippage η_0 vs. the number of consecutive turn-by-turn energy modulations, normalized to the maximum value of each dataset for clarity. The simulation starts from a non-microbunched equilibrium longitudinal electron distribution and uses a simplified standard longitudinal kick map with longitudinal quantum diffusion included on each revolution. The simulation assumes a linear, non-momentum dependent phase slippage $\eta(\delta) = \eta_0$, a laser modulation strength of $eU_{\mathrm{laser}}/E_0 = 6 \cdot 10^{-5}$, a zero-current beam energy spread of $\sigma_\delta = 1.8 \cdot 10^{-4}$ and a turn-by-turn phase-constant modulation ($f_{\mathrm{laser}}/f_{\mathrm{rev}} = N, N \in \mathbb{N}$).

Note the shift of the first maximum to a larger number of modulations with lower phase slippage as the rotation of longitudinal phase space becomes slower, as well as the oscillating pattern connected to synchrotron oscillations performed by particles within individual microbunches.

EXPERIMENTAL RESULTS

Within the presented experimental setup at the MLS, we aim to reproduce the results from simulation shown above. Since the setup does not allow simultaneous laser modulation and detection of undulator radiation, we vary the number of total consecutive laser shots and observe the coherent undulator radiation on the revolutions directly following the cessation of modulation.

Figure 3 shows an exemplary experimental signature obtained from a photodiode detector at the undulator beamline of the MLS. In the example, coherent emission is detected following energy modulation on three consecutive revolutions of the storage ring (revolution numbers -3 through -1). At the detector gate trigger (blue), the sensitivity of the detector is increased by a factor of approximately 10^8 to enable detection of undulator radiation using fast-switching Pockels cells on revolution numbers 0 and onwards. The storage ring is filled with a bunch train of 20 uniformly populated bunches out of the total possible 80 bunches. Rising above the normal incoherent undulator radiation from the bunch train is the coherent emission of the modulated bunch. To quantify the exclusively coherent part of the radiation power, the incoherent power level taken from the unmodulated bunches is subtracted from the total power level observed for the modulated bunch.

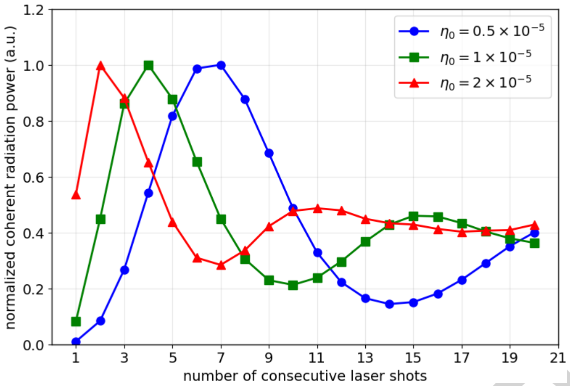

Figure 2: Simulated coherent radiation power vs. number of consecutive laser modulations for different values of the phase slippage η_0.

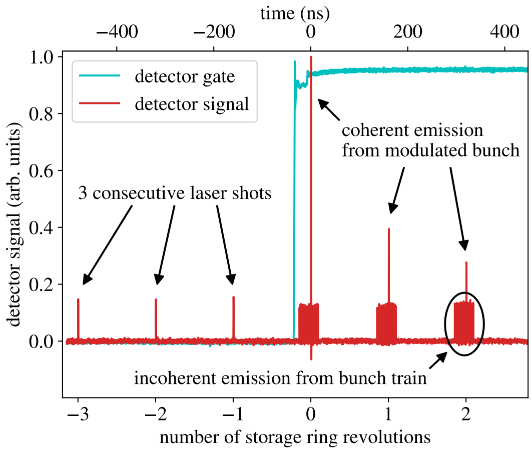

Figure 3: Exemplary experimental signature in SSMB PoP phase II.

Varying number of laser modulations

Figure 4 shows the measured coherent undulator radiation power as a function of the number of applied laser modulations. To enable comparison with the simulation (Fig. 2), each dataset is presented normalized to its maximum sample. The overall pattern can be seen to be reproduced for three different bunch charges, and is qualitatively as expected: We see very weak coherent emission with one modulation, a maximum at three modulations and afterwards a weak oscillation with a minimum around 5 and another maximum around 8 modulations.

There are two main quantitative inconsistencies with the simulation: Firstly, the location of the first minimum does not fit to the first maximum when comparing to Fig. 2. This may be explained with the impact of significant higher-order nonlinear phase slippage as well as a turn-by-turn phase drift between laser and electron beam, which is not excluded in the experiment. Secondly, for large number of modulations, the coherent radiation power does not settle on a medium level as in simulation, but on a rather high level. However, the fact that in experiment significant coherent radiation can be observed after a large number of consecutive laser modulations, up to 1000, is encouraging for SSMB PoP phase II, as it may indicate that the electrons have already reached a quasi-steady state within the microbunches.

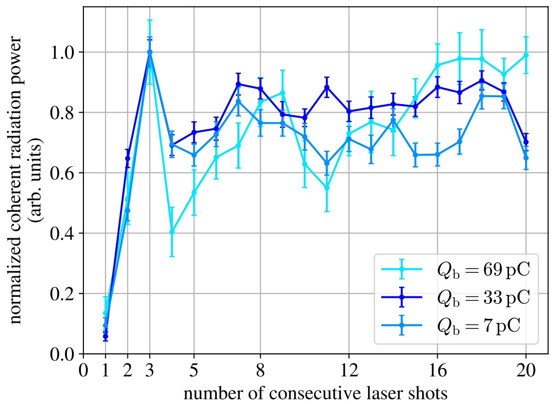

Figure 4: Coherent radiation power vs. number of consecutive laser modulations for constant phase slippage reproduced for three different bunch charges.

Figure 5 shows four additional measurements of coherent radiation power vs. number of consecutive energy modulations for different values of the linear phase slippage η_0, varied by symmetrically adjusting quadrupole magnet currents at positions of high dispersion. The change in phase slippage is given relative to the state presented in Fig. 4, obtained by comparing the relative changes of quadrupole magnet currents to the storage ring model.

Again, the overall trend qualitatively fits to the expectation from simulation: For smaller η_0, the position of the first maximum of coherent radiation power shifts to larger numbers of consecutive laser modulations (compare Fig. 2). However, there is no clear indication of an oscillating pattern beyond the first five to ten modulations. Also, the quantitative change of η_0 does not fit to the simulation: Where in experiment a total change of $\Delta\eta_0 \approx 10^{-4}$ was applied to obtain a shift of the first maximum of coherent emission from 9 modulations to 2 modulations, in simulation the same can be achieved by a change of only $\Delta\eta_0 = 2 \cdot 10^{-5}$. Again, the nonlinear phase slippage that was neglected in simulation may play a role here, possibly even involving alpha bucket dynamics with negative phase slippage $\eta_0 < 0$ [16]. There may also be further effects in play that affect especially the coherent radiation emitted after a large number of laser modulations, considering that the behavior of the onset of microbunching for the first few modulations fits to the simulation best.

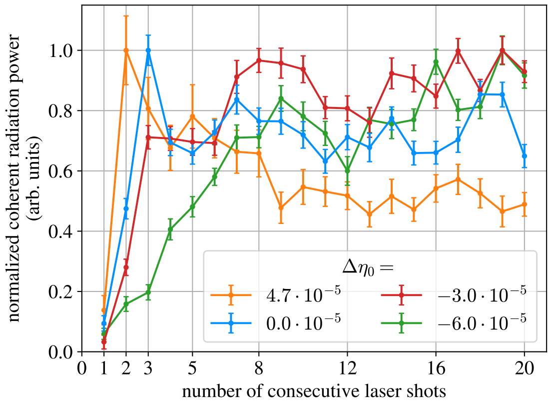

Figure 5: Coherent radiation power vs. number of consecutive laser modulations for different values of the phase slippage, with estimated difference to the state represented in Fig. 4 denoted as $\Delta\eta_0$.

CONCLUSION

The second phase of the steady-state microbunching proof-of-principle experiment has successfully begun at the Metrology Light Source. Detection of coherent radiation from a microbunched electron following multiturn laser energy modulation is routinely possible, allowing systematic studies to commence. In a first successful reproduction of the theoretical expectations, the strength of microbunching starting with an equilibrium beam for increasing number of successive energy modulations has been shown to qualitatively agree with simulation results of this process. The encoded pattern of synchrotron oscillations within individual microbunches is observed in experiment with limited significance, major remaining inconsistencies are the quantitative dependence on phase slippage and the behavior for large numbers of consecutive energy modulations. Both may be influenced by higher order contributions of the nonlinear phase slippage, such as alpha bucket dynamics [16], complicating the longitudinal phase space. Another important milestone yet to be shown is the influence of the turn-by-turn phase relation between laser modulation field and electron beam arrival time.

Overall, the results presented in this work constitute an important early success of the SSMB PoP phase II campaign, to be improved upon in upcoming intensified studies.

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