

LASER MODULATOR FOR SSMB USED AS A DIAGNOSTIC TOOL

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Abstract

At the Metrology Light Source in Berlin, the concept of Steady-state microbunching (SSMB) is evaluated in a proof-of-principle (PoP) experiment. SSMB has been proposed to deliver kilowatt level average power EUV radiation from an electron storage ring. In the PoP experiment, an energy modulation is impressed onto the electron beam using an infrared laser pulse co-propagating inside an undulator. We show that the beam energy can be measured absolutely by detuning the undulator gap from optimum resonance and observing the intensity of the resulting coherent synchrotron radiation.

INTRODUCTION

Steady-state microbunching (SSMB) has been proposed [1, 2] as a new kind of storage ring based synchrotron radiation source that promises to generate high brilliance, high average power coherent radiation at wavelengths as short as the extreme ultraviolet (EUV). An SSMB storage ring would indefinitely store nanometer-length microbunches, and thus benefit from both the coherence of radiation generated from microbunches and the inherently high repetition rate of a storage ring.

Extensive theoretical studies on SSMB and related effects are ongoing [3–11], and the viability of SSMB is tested in a proof-of-principle (PoP) experiment at the Metrology Light Source (MLS) [12–17].

The MLS is an electron storage ring owned by PTB and operated by HZB in Berlin, Germany [18, 19]. It is uniquely suited as a testbed for SSMB because it has been designed and optimized for low alpha operation, and as such offers the necessary operational flexibility with dedicated sextupole and octupole magnet families to control the higher order momentum compaction. Table 1 lists the most important storage ring parameters of the MLS for standard operation and the SSMB PoP experiment.

Table 1: Machine parameters of the MLS storage ring for standard user operation and the SSMB PoP experiment

Parameter	Symbol	User 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
Phase slippage	η_0	0.03	< $2 \cdot 10^{-5}$

SETUP AND THEORETICAL ASPECTS

Experimental Setup at the MLS

In the SSMB PoP experiment as currently set up at the MLS, a simplified SSMB scheme is realized. Figure 1 shows a sketch of the setup. A single shot laser is steered to co-propagate with the electron beam through the only undulator installed at the MLS (for some important parameters see table 2).

The whole storage ring optics are set up such that the energy modulation is transformed into physical microbunching after one revolution, this is achieved by applying quasi-isochronous optics. The same undulator used for modulation is also employed to generate coherent radiation, which is detected at the undulator beamline using a fast photodiode. Detection of coherent radiation at the first undulator harmonic is non-trivial, as the strong modulation laser pulse is also present in the detection path at the same wavelength [13, 14].

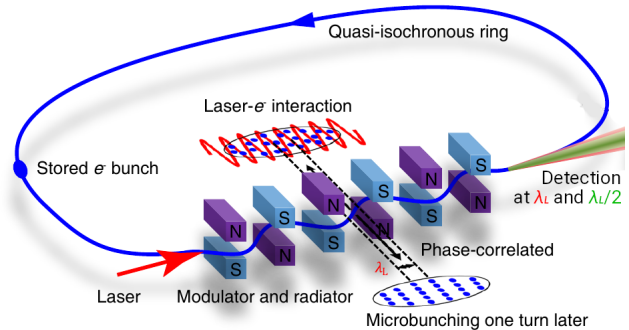


Figure 1: Schematic setup of the SSMB PoP experiment.

Table 2: Undulator and laser parameters for the SSMB PoP experiment.

Parameter	Symbol	Value
Undulator period	λ_u	125 mm
Number of periods	N	30
Laser wavelength	λ_L	1064 nm
Laser repetition rate		1.25 Hz
Maximum laser pulse energy	$E_{L,max}$	400 mJ
Undulator gap at λ_L	$g(\lambda_L)$	72.1 mm

Energy Modulation in an Undulator

Undulator radiation is restricted to certain wavelengths λ_r given by the well known resonance condition

$$\lambda_r = \frac{\lambda_u}{2\gamma^2} \frac{1}{n} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right) \quad (1)$$

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that arises from interference between photons emitted in different undulator periods spaced apart by λ_u . For the problem of transferring energy from a radiation field to the electron beam inside an undulator, one can see that the same resonance condition (1) has to be fulfilled for the wavelength of the external radiation field λ_L (typically a laser).

The spectral distribution of undulator radiation in the vicinity of λ_r is commonly described by a lineshape function L that only depends on the number of undulator periods N . For on-axis radiation ($\theta = 0$), we can write it as

$$L_{\lambda_r}(\lambda) = \frac{\sin^2(N\pi(\lambda - \lambda_r)/\lambda_r)}{N^2 \sin^2(\pi(\lambda - \lambda_r)/\lambda_r)}, \quad (2)$$

and it yields the reduction of radiation power at wavelength λ relative to λ_r , $L_{\lambda_r}(\lambda) = P(\lambda)/P(\lambda_r)$. An example for the case of the MLS undulator is shown in the top left of Fig. 2.

By the same logic that allowed us to use the resonance condition (1) also for the case of energy modulation, we can now also apply the lineshape function (2) to describe how efficient the energy modulation is for non-optimal resonance between laser and undulator. Because we will keep the laser wavelength λ_L constant and vary the undulator resonant wavelength λ_r , we reverse the notation of equation (2) and write a lineshape function $L_{\lambda_L}(\lambda_r)$.

To model the energy modulation we will use a modulation amplitude A that is proportional to the electric field of the laser $\mathcal{E}_L$, which in turn is proportional to the square root of the instantaneous laser power: $A \propto \mathcal{E}_L \propto \sqrt{P_L}$. Because the lineshape function makes a statement about radiation power, we write for the modulation amplitude as a function of undulator resonant wavelength:

$$A(\lambda_r) = A_{\max}(P_L) \cdot \sqrt{L_{\lambda_L}(\lambda_r)}, \quad (3)$$

with the optimum modulation amplitude $A_{\max}$ at $\lambda_r = \lambda_L$.

Microbunching Formation and Coherent Radiation

For a single particle, the energy modulation occurring on revolution number $m = 0$ can be modeled as

$$\delta_{m>0} = \delta_0 + A \sin(k_L z_0), \quad (4)$$

where $\delta = \Delta p/p_0$ is the momentum deviation relative to the reference particle with momentum p_0 . δ_0 is the initial momentum deviation of the particle before modulation, and z_0 is the initial longitudinal position. The effect of the energy modulation on subsequent revolutions can be written as

$$z_{m+1} = z_m - C_0 \eta \delta_{m+1}, \quad (5)$$

with the circumference of the storage ring C_0 and the phase slippage factor η that gives the relation between relative change of revolution time and momentum deviation, $\Delta T/T_0 = \eta \delta$, where T_0 is the revolution time of the reference particle.

It should be noted here that for successful microbunching formation in the SSMB PoP experiment, the phase slippage

needs to be very small, $\eta \lesssim 2 \cdot 10^{-5}$. In this regime, its dependence on the particle momentum becomes important [20]. For the sake of simplicity, in this paper we nevertheless assume a constant phase slippage $\eta(\delta) \approx \eta_0 = \text{const.}$, even though the nonlinearities of the phase slippage function can play an important role for SSMB [17].

To describe how strongly microbunching is pronounced at a longitudinal wavenumber k , it is useful to introduce the bunching factor $b(k)$ that is defined as the Fourier transform of the longitudinal particle distribution $\rho(z)$:

$$b(k) = \int_{-\infty}^{\infty} e^{-ikz} \rho(z) dz. \quad (6)$$

Coherent radiation power is proportional to the bunching factor squared, $P_{\text{coh}}(k) \propto |b(k)|^2$.

Under certain assumptions about the initial particle distribution, it can be shown [9] that the microbunching process modeled by (4) and (5) yields a nonzero bunching factor only at integer harmonics of the laser wavenumber. We can write for the bunching factor on the n -th laser harmonic and m -th revolution after modulation

$$b_{n,m} \propto J_n(nmk_L \eta_0 C_0 A), \quad (7)$$

where J_n denotes a Bessel function of the first kind. An example of $b_{1,1}$ varying with A is shown in the top right of Fig. 2.

Inserting (3) into (7), we can find an expectation for the coherent radiation power vs. undulator resonant wavelength. For varying $A_{\max}$ this expectation is shown in the bottom plot of Fig. 2 (first harmonic, one revolution after modulation).

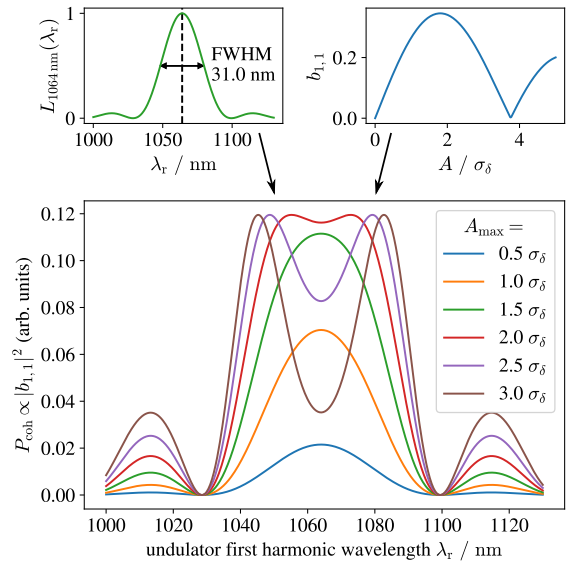


Figure 2: Combining undulator lineshape function (top left) with calculated bunching factor (top right) to yield coherent radiation power vs. undulator resonant wavelength for different laser modulation depths (bottom). Modulation amplitudes are given relative to the beam energy spread σ_δ .

EXPERIMENTAL RESULTS

Variation of Laser Pulse Energy

The total pulse energy E_L of the modulation laser can be manipulated in the experiment by rotating a half-wave plate installed between crossed polarizers, and measured using a laser power meter. The temporal laser pulse shape is constant to good accuracy, thus allowing us to assume that the total pulse energy is proportional to the instantaneous laser power incident on the electron bunch in the modulator, $E_L \propto P_L \propto A_{\max}^2$.

We vary the laser pulse energy and perform scans of the undulator gap around its optimum value for modulation at the laser wavelength of $\lambda_L = 1064$ nm, observing the coherent synchrotron radiation emitted one revolution after modulation. The results are shown in Fig. 3. A comparison with in Fig. 2 shows a good agreement with the expected behavior. The region of acceptable undulator resonant wavelength in Fig. 3 exhibits the expected width of FWHM ≈ 30 nm, and the relative changes of the curves for varying laser power are as expected, in particular with the observed double peak structure for the highest laser pulse energies.

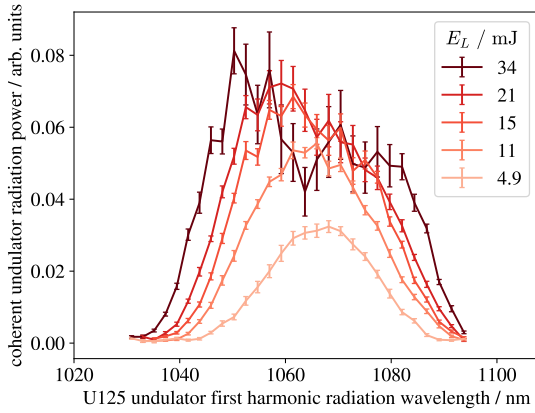


Figure 3: Measured coherent radiation power vs. undulator resonant wavelength (converted from undulator gap) at different laser pulse energies.

Absolute Measurement of Beam Energy

The horizontal axis in Fig. 3 shows a radiation wavelength instead of the undulator gap that is used during the measurement. The wavelength is converted from the undulator gap using the resonance condition (1). For this conversion to succeed, the electron beam energy has to be known to high accuracy. We can however also extract the absolute beam energy from the undulator gap scan results by making use of the fact that we exactly know the laser wavelength λ_L . Because optimum modulation has to occur at $\lambda_r = \lambda_L$ (if there is no double peak feature due to overbunching as depicted for some of the curves in Fig. 2), we can infer that the undulator gap where maximum coherent radiation power is measured corresponds to $\lambda_r = \lambda_L$.

To accurately extract this optimum gap from the measured data we employ Gaussian fits (using the position of the resulting Gaussian curve). In order for the Gaussian fits to well represent the data (as is the case in the examples shown in Fig. 4), the laser pulse energy should not be too high (for example, the lowest three values of E_L in Fig. 3 work well).

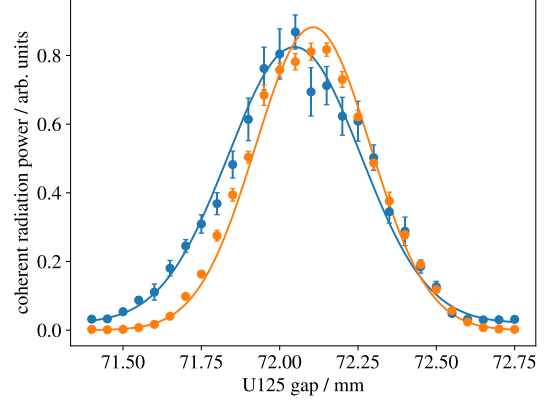


Figure 4: Two exemplary undulator gap scans (indices 1 and 3 in Figs. 5 and 6, scaled arbitrarily) and corresponding Gaussian fits. The two scans shown are conducted at slightly different beam energy (difference on the order of 10^{-3}).

The two measurements depicted in Fig. 4 were conducted at slightly different beam energies. The difference in optimal undulator gap can be clearly resolved. The energy change is achieved at constant bending magnet flux by detuning the frequency of the rf wave in the cavity, thereby adjusting the revolution time of the particles; this change of revolution time then corresponds to a momentum change via the phase slippage factor. This technique to manipulate the electron beam energy is regularly utilized in the SSMB PoP experiment to optimize conditions for microbunching, as it also has a significant effect on higher order phase slippage.

Having obtained values for the optimum undulator gap, an existing measurement of undulator magnetic field strength vs. gap can be used to convert these values into undulator strengths K . Then, the resonance condition (1) can be used to calculate the beam energy from K and the known laser wavelength. For this, the opening angle is assumed to be $\theta = 0$, because the laser is aligned to be parallel to the electron beam.

Figure 5 depicts absolute measurements of the electron beam energy obtained in this way, showing multiple independent undulator gap scans conducted at slightly different conditions.

Marked in red is the energy $E_{\text{CBS}} = 254.31$ MeV obtained previously [18] from Compton backscattering (CBS) measurements in the 250 MeV machine state used for the SSMB PoP experiment. It can be seen that the values measured using the undulator gap scans correspond to E_{CBS} to high accuracy.

The significant deviations of some data points can be explained by the intentional energy offsets induced from rf

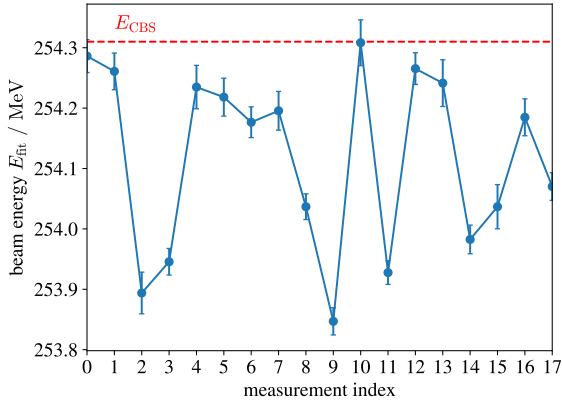


Figure 5: Beam energy extracted from multiple undulator gap scans. The energy measured using Compton backscattering (CBS) is marked in red. Each measurement is conducted at a slightly different, negative energy offset from the design energy (see text and Fig. 6).

frequency detuning mentioned earlier. This is depicted in Fig. 6, where the relative deviation of the measured beam energy from E_{CBS} is compared to a relative momentum deviation δ calculated from horizontal orbit offset measured at a position with horizontal dispersion D_x .

It is clear that both methods show the same trend in relative energy deviation. The overall mismatch of the absolute values can be attributed to a systematic error in determination of δ from the orbit position, as the value D_x is not known to high accuracy and there is an uncertain offset on Δx .

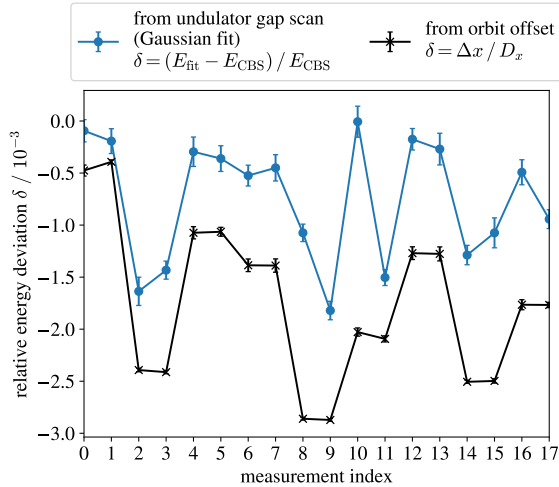


Figure 6: Comparison of relative energy deviation calculated from undulator gap scan results (Fig. 5) and horizontal orbit offset at a position with dispersion.

CONCLUSION

We have shown that the properties of a laser modulator can be used in combination with the microbunching process of the SSMB PoP experiment to allow an accurate and absolute

measurement of the electron beam energy at the Metrology Light Source.

The resolution of the energy measurement obtained by the presented method is currently limited to approximately 2 ‰. There is an uncertainty contributed by the fluctuations of the detected coherent radiation signal, and this could be improved upon. However, there is a conceptual resolution limit given by the width of the lineshape function, which depends on the number of undulator periods in the modulator. An undulator with more periods would thus be beneficial to increase the resolution.

Currently, the technique is limited at the MLS to measure small variations of the beam energy around 250 MeV, as a machine state to support microbunching is only established at this energy. This may change in the future, as there are plans to also enable the SSMB PoP experiment to be run at different beam energies.

However, we point out that the microbunching process of the SSMB PoP experiment is not an inherent part of the energy measurement technique, it is only utilized to observe the efficiency of the laser modulation. Any method that can quantify the impact of such a modulation on the beam can be used to enable an energy measurement, and with a sufficiently tunable undulator the laser modulation itself can be imposed over a wide range of electron beam energies.

While Compton backscattering setups are superior, whenever a laser modulator setup is already available, the technique presented here may be low-effort alternative also outside of the scope of SSMB. It is also useful whenever CBS is unavailable, as is the case for the SSMB PoP experiment at the MLS, where a use of the CBS setup would require a partial dismantling of the SSMB setup.

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