COHERENT HARMONIC GENERATION IN THE PRESENCE OF SYNCHRONIZED RF PHASE MODULATION AT DELTA*

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Abstract

At the 1.5-GeV synchrotron light source DELTA operated by the TU Dortmund University, ultrashort coherent pulses in the VUV and THz regime are generated via coherent harmonic generation (CHG). The intensity of the light depends strongly on the quality of the laser-electron interaction and therefore on the energy spread and density of the electron bunches. In 2014, a significant increase of the CHG intensity was observed by phase-modulating the RF cavity voltage, which is routinely used to prolong the beam lifetime. RF phase modulation can generate multiple stable regimes (islands) in longitudinal phase space when run near an integer multiple of the synchrotron frequency resulting in a modulation of the electron density and energy spread. A numerical simulation supporting the experimental observations is presented.

INTRODUCTION

At the synchrotron light source DELTA operated by the TU Dortmund University, ultrashort and coherent radiation pulses in the VUV regime are generated using coherent harmonic generation (CHG) [1,2]. An ultrashort laser pulse from a 800-nm femtosecond laser system co-propagates with an electron bunch through an undulator (modulator). This results in an energy modulation of a small fraction of the bunch since the bunch is more than 1000 times longer than the laser pulse. A dispersive chicane generates microbunches in the energy-modulated part of the electron bunch. These microbunches are separated by one laser wavelength and lead to coherent emission of ultrashort VUV pulses when propagating through a second undulator (radiator).

At DELTA, a 500-MHz DORIS-type cavity is in operation. The cavity voltage is routinely phase-modulated to increase the beam lifetime by about 10 % to 15 % during standard user operation. If the modulation frequency is close to an integer multiple of the synchrotron frequency (integer resonance), the longitudinal electron motion is excited. The excitation affects the energy spread as well as the electron density and may cause the creation of multiple stable regimes (islands) in longitudinal phase space depending on the modulation parameters. The RF phase modulation is run near the 2nd integer reducing the effective loss rate by the Touschek effect [3] due to a reduced electron density. Moreover, the stability of the beam is improved as longitudinal coupled-bunch instabilities are suppressed by the phase modulation [4,5].

A future goal at DELTA is to provide ultrashort pulses via CHG during standard user operation which requires a hybrid filling pattern. Being capable of operating CHG in the presence of phase modulation might therefore be a necessity in view of the beam lifetime. In 2014, it was found that this operation is not only possible but also an intensity increase of the CHG intensity is achievable [6,7].

CHG WITH SYNCHRONIZED RF PHASE MODULATION

The coherent radiation power generated by CHG reads

$$P_{\mathrm{coh}} = N^2\,|b_n|^2\,P_{\mathrm{e}}$$

with N being the number of electrons, b_n being the bunching factor and P_{e} being the radiation power from a single electron. The bunching factor b_n is a measure of the coherent radiation emitted at the harmonic n of the laser wavelength λ. The absolute value $|b_n|$ ranges between 0 and 1. It decreases exponentially with increasing energy spread $b_n \propto \exp\left(-\sigma_E^2\right)$ [8]. Hence, the influence of RF phase modulation on the energy spread as well as the density may modify the CHG intensity.

In addition to CHG, the emission of coherent THz radiation is observed. The dispersion in the bending magnets leads to the longitudinal displacement of the energy-modulated electrons after the laser-electron interaction. This creates a dip in the electron density which gives rise to coherent emission of THz radiation in the bending magnets [9–11].

At DELTA, a sinusoidal phase modulation is applied to the accelerating RF voltage

$$U_{\mathrm{RF}}(t) = U_0 \sin\left(\omega_{\mathrm{RF}} t + A_{\mathrm{m}} \sin\left(\omega_{\mathrm{m}} t\right)\right) \qquad (1)$$

where U_0 is the peak voltage , ω_{RF} is the RF angular frequency, A_{m} is the modulation amplitude and ω_{m} is the modulation angular frequency. The synchrotron frequency is approximately $f_{\mathrm{s}} = 1/T_{\mathrm{s}} = 16\,\mathrm{kHz}$ with a cavity power of $P_{\mathrm{RF}} = 25\,\mathrm{kW}$ at DELTA. At the 2nd integer resonance ($\omega_{\mathrm{m}} \approx 2\omega_{\mathrm{s}}$), the bunch splits up into multiple islands (see Fig. 1).

The rotation frequency of the islands in phase space may differ from the synchrotron frequency. The frequency, e.g., reads $\omega_{\mathrm{m}}/2$ at the 2nd integer resonance. In order to have a stable laser-electron interaction when operating CHG and RF phase modulation simultaneously, the rotation frequency

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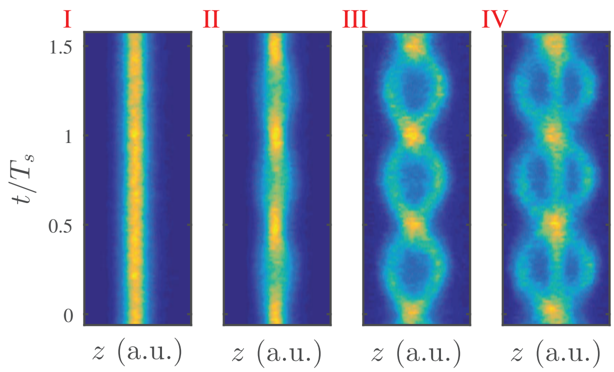

Figure 1: Streak camera images of the electron bunch at 2nd integer resonance [6]. I: The modulation amplitude is zero. No effects on the beam are visible. II: Slightly above the resonance frequency, two islands exist although they are too close to be distinguishable. The bunch *breathes*, i.e., it becomes longer and shorter. III: The bunch splits up into two islands slightly below the resonance frequency. IV: The center becomes stable causing the creation of a 3rd island if the modulation frequency is decreased further.

has to be an integer multiple of the laser repetition rate, which is 1 kHz in the case of DELTA. If this condition is not exactly matched, the laser samples different phases of the synchrotron period. In 2014, it was found that in the breathing regime near the 2nd integer resonance (see Fig. 1 plot II) the CHG and THz signal have a higher intensity than without RF phase modulation at specific phases (see Fig. 2) [6, 7]. Increases of roughly 30 % were achieved. In the breathing regime, the bunch is particularly short at one point during the synchrotron period and has a large energy spread. A quarter synchrotron period later, the bunch length is large and the energy spread is small. Since the CHG intensity mainly depends on the particle density, an increase of the intensity is observed although the bunching factor might be smaller than in the normal case. The 180° phase difference between the two signals results from the THz intensity being more sensitive to the energy spread than to the electron density [11].

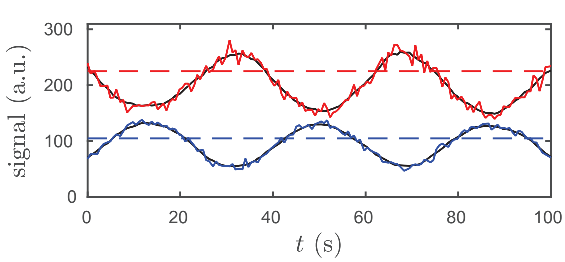

Figure 2: The laser is sampling different phases of the synchrotron period of the breathing regime at the 2nd integer resonance [7]. The CHG signal (red) is phase-shifted by 180° with respect to the THz signal (blue). At specific phases of the synchrotron period, both signals are more intense than without RF phase modulation (dashed lines).

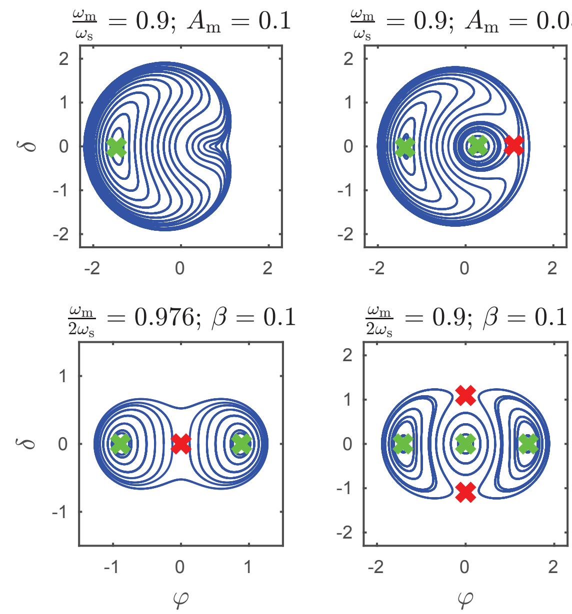

Figure 3: Different configurations in phase space for the 1st (top) and 2nd (bottom) integer resonance. The stable fixed points are marked in green and the unstable fixed points in red. At specific parameter sets, the bunch splits up into two islands at the 1st integer resonance (top right). At the 2nd integer resonance, there is the possibility to generate either two or three islands ($\beta = A_m \tan \phi_s$).

HAMILTONIAN OF THE LONGITUDINAL PHASE SPACE

In the case of a sinusoidal RF phase modulation according to Eq. (1) and without radiation damping, the Hamiltonian for the longitudinal particle dynamics reads

$$H = \frac{1}{2}\omega_s \delta^2 - \frac{\omega_s}{\cos\phi_s}[\cos(\phi_s + \varphi + A_m \sin(\omega_m t)) + \varphi \sin\phi_s] \quad (2)$$

with ω_s being the synchrotron frequency, ϕ_s being the synchronous phase angle, φ being the deviation from the synchronous phase angle and $\delta = (h\eta/\nu_s)\Delta p/p_0$ being the normalized momentum. Here, η is the slippage factor, h is the harmonic number and ν_s is the synchrotron tune.

Starting from this Hamiltonian, the phenomenon of island formation is calculable by switching to action-angle variables and into a rotating reference frame [12]. In other publications [4, 13–15], Hamiltonians restricted to the 1st, 2nd and 3rd integer resonance are derived. Figure 3 presents different configurations in phase space for different parameter sets at the 1st and 2nd integer resonance.

In general, the Hamiltonian in rotating action-angle variables is m-fold rotational symmetric with m being an integer indicating the modulation frequency resonance ($\omega_m \approx m \cdot \omega_s$). Islands exist at the locations of stable fixed points of the respective Hamiltonian [4, 13–15].

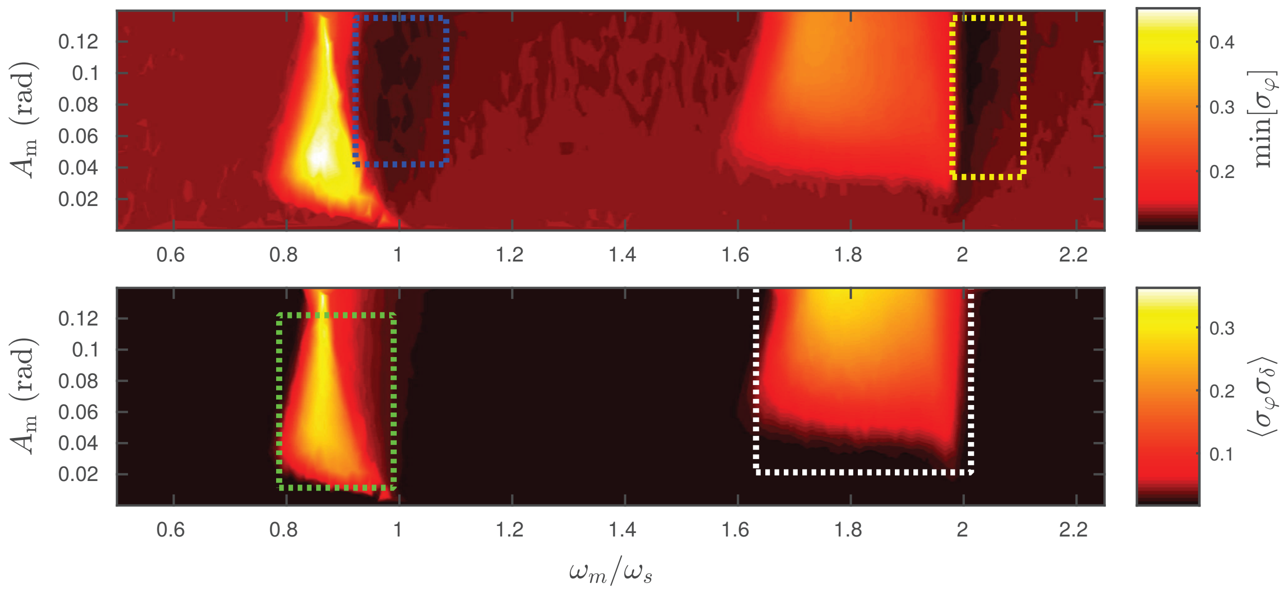

Figure 4: Top: The minimum bunch length $\min[\sigma_\varphi]$ during the synchrotron period as function of A_m and ω_m. Within the blue and yellow framed areas, the minimum bunch length is smaller than the bunch length of the normal bunch. Bottom: The time-averaged product of the bunch length and momentum spread $\langle\sigma_\varphi\sigma_\delta\rangle$ as function of A_m and ω_m. The green and white framed areas indicate the parameter sets at which the beam lifetime is expected to be particularly large [12].

SIMULATIONS

Applying the semi-implicit Euler method to the Hamiltonian of Eq. (2) and taking radiation damping into account leads to the mapping equations [12, 13]

$$\varphi_{n+1} = \varphi_n + 2\pi\nu_\mathrm{s}\delta_{n+1} \tag{3}$$

$$\delta_{n+1} = \delta_n + \frac{2\pi}{\cos\phi_\mathrm{s}}(\sin\phi_\mathrm{s} - \sin(\phi_\mathrm{s} + \varphi_n + A_\mathrm{m}\sin\omega_\mathrm{m}t)) + \mathrm{rand}(\mu_\mathrm{N}, \sigma_\mathrm{N}) \tag{4}$$

with $\mathrm{rand}(\mu_\mathrm{N}, \sigma_\mathrm{N})$ indicating a random number following a normal distribution with mean $\mu_\mathrm{N} = -2\alpha_s T_0 \delta_n$ and standard deviation $\sigma_\mathrm{N} = 2\sqrt{\alpha_s T_0}\sigma_\delta$. Here, α_s is the longitudinal damping constant, T_0 is the revolution time and σ_δ is the normalized relative momentum spread. The normal distribution models the stochastic nature of radiation damping. The Eqs. (3) and (4) allow for the tracking of a single electron with the initial phase-space coordinates (φ_n, δ_n) to the new coordinates $(\varphi_{n+1}, \delta_{n+1})$ at the next revolution.

In order to find optimum settings for a potential increase of the CHG intensity, particle tracking for different parameter sets of the phase modulation was performed. The modulation frequency ω_m and the modulation amplitude A_m were varied in the range of 0.5 to $2.25 \cdot \omega_\mathrm{s}$ and 0 to 0.15 rad, respectively. Higher-order resonances do not support any increase of the electron density at one point during the synchrotron period due to the higher-order rotational symmetry. Hence, the simulation covers the 1st and 2nd resonances only. The top plot of Fig. 4 shows the minimum bunch length during one synchrotron period $\min[\sigma_\varphi]$. Within the blue and yellow framed areas, the minimum bunch length is smaller than without RF phase modulation. Nevertheless, the time-averaged product of the bunch length and the momentum spread $\langle\sigma_\varphi\sigma_\delta\rangle$ is larger than in the case of the normal bunch (see bottom plot of Fig. 4). The increase of the CHG and THz intensity presented in Fig. 2 was observed in the yellow framed area. It was not yet tried to operate the phase modulation at the 1st integer resonance with the goal to increase the intensity of the laser-induced radiation. Within the green and white framed area in the bottom plot of Fig. 4, the beam lifetime is expected to be particularly large since the time-averaged phase-space area occupied by electrons is maximum. This indicates a large bunch length and large momentum acceptance.

CONCLUSION

The simulation of the particle trajectories in phase space supports the assumption of a shortened bunch length in the region of the 2nd integer resonance. In the future, it has to be checked experimentally whether a similar increase is achievable at the 1st integer resonance. The previous analysis is based on the general parameters of bunch length and momentum spread. These are vague parameters to determine a potential increase of the laser-induced signals since the laser-electron interaction occurs only in a mere fraction of the electron bunch. In the future, an analysis based on the Vlasov-Fokker-Planck (VFP) equation will be carried out. The numerical integration of the VFP equation has already been successful, although this is not presented here.

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