ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB233

# EXCITATION OF MICRO-BUNCHING IN SHORT ELECTRON BUNCHES USING RF AMPLITUDE MODULATION

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*Abstract*

In its short-bunch operation mode, the KIT storage ring KARA provides picosecond-long electron bunches, which emit coherent synchrotron radiation (CSR) up to the terahertz frequency range. Due to the high spatial compression under these conditions, the self-interaction of the bunch with its own emitted CSR induces a wake-field, which significantly influences the longitudinal charge distribution. Above a given threshold current, this leads to the formation of dynamically evolving micro-structures within the bunch and is thus called micro-bunching instability. As CSR is emitted at wavelengths corresponding to the spatial dimension of the emitter, these small structures lead to an increased emission of CSR at higher frequencies. The instability is therefore deliberately induced at KARA to provide intense THz radiation to dedicated experiments. To further increase the emitted power in the desired frequency range, we consider the potential of RF amplitude modulations to intentionally excite this form of micro-bunching in short electron bunches.

## INTRODUCTION

The micro-bunching instability limits the operation of modern storage rings with short electron bunches. At high bunch currents, it leads to an increased energy spread, a dynamically varying longitudinal charge distribution and fluctuating emission of coherent synchrotron radiation (CSR). It is generally accepted that the source of the phenomenon is the formation of micro-structures within the bunch arising from the self-interaction of the beam with its own emitted CSR [1]. As this interaction typically occurs in the microwave frequency range it also referred to as a microwave instability. Yet, the presence of these small structures on the beam can lead to an increased emission of CSR at spectral frequencies up to the THz regime. The thus generated CSR can be provided to dedicated experiments with a demand for high intensity THz radiation and is therefore deliberately induced at the KIT storage ring KARA in a short-bunch operation mode [2]. While the formation of micro-structures is quite desirable in this case, further control of these dynamics offers the potential to expand its use cases and to tailor the CSR emission to individual applications. The notion of using RF phase modulations to influence the micro-bunching dynamics was already explored in [3–5].

In previous work [6, 7], we identified the CSR-generated perturbation of the restoring force excerted by the RF system as a critical component for the formation process of the occurring micro-structures. This immediately suggests the use of an RF amplitude modulation to amplify or mitigate the perturbation and thereby drive the micro-bunching dynamics. We will discuss how this approach can be used to excite different forms of micro-bunching within short electron bunches, either by driving the already existing structures due to the micro-bunching instability or by imprinting an entirely new set of micro-structures on the beam. The general concept is demonstrated in simulations using the Vlasov-Fokker-Planck (VFP) solver Inovesa [8] and verified in first experiments at KARA.

## EXCITATION AT INSTABILITY FREQUENCY

Directly above the instability threshold current, the micro-bunching dynamics are typically found to be quite regular, that is, the micro-structures form and propagate in a highly repetitive and self-consistent manner. While the structures are most pronounced at the head of the bunch ($z > 0$), their maximum amplitude stays nearly constant across time and the resulting dynamics are merely caused by their rotation and propagation in the longitudinal phase space (see Fig. 1).

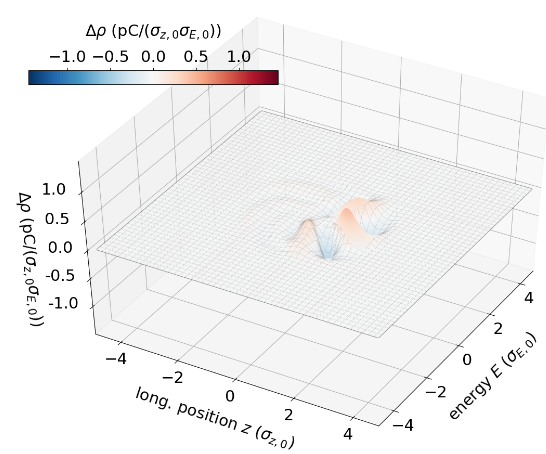


Figure 1: Above the threshold current, the micro-bunching instability causes the formation of micro-structures in the longitudinal phase space. Shown is a snapshot of the charge distribution $\rho(z, E, t_i)$ with the temporal average subtracted $\Delta\rho(z, E, t_i) = \rho(z, E, t_i) - \bar{\rho}(z, E)$ to visualize the occurring micro-structures. The illustrated dynamics have been simulated with Inovesa.

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12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB233



As a result, the emitted CSR power as well as other derived beam properties like the energy spread or the bunch length oscillate with one particular frequency $f_{\text{inst}}$, forming an almost sinusoidal signal. The CSR wake potential and the resulting perturbation of the restoring force are also subject to these dynamics. In particular, this means the gradient of the effective potential

$$V_{\text{eff}}(q,t) = V_{\text{RF}}(q,t) + V_{\text{CSR}}(q,t) \ , \qquad (1)$$

is fluctuating with the same frequency. One straight-forward approach to interact with these dynamics is thus to modulate the RF amplitude at the natural instability frequency $f_{\text{inst}}$ to further drive the perturbation. Figure 2 illustrates the results obtained by testing this idea in simulations.

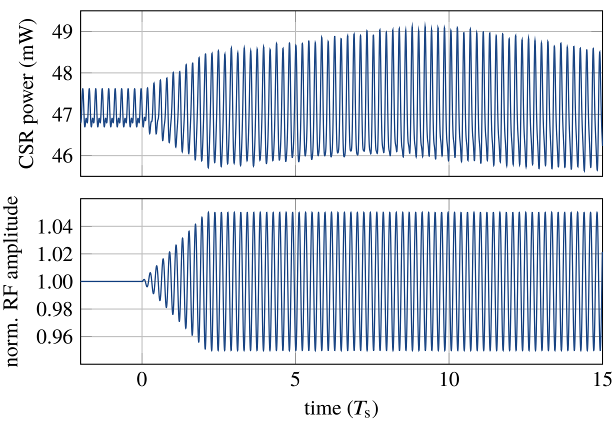


Figure 2: A modulation of the RF amplitude with five percent of the main RF voltage $V_0$ at the instability frequency $f_{\text{inst}}$ (bottom) leads to an increased oscillation of the CSR power signal (top).

The RF amplitude was modulated with five percent of the main accelerating voltage $V_0$ at instability frequency. After the modulation is applied at $t = 0$, the oscillation amplitude of the CSR power increases significantly and eventually follows the excitation by the RF signal. After a subsequent transient period, the dynamics stabilize at similar behavior compared to the situation without the RF modulation ($t < 0$), but at a larger oscillation amplitude. This corresponds to a growth of the micro-structures within the bunch as illustrated in Fig. 3. While the overall shape is nearly identical to the structure depicted in Fig. 1, the maximum amplitude is increased by nearly 50 percent.

## EXCITATION NEAR 3rd HARMONIC

In a scan across different modulation frequencies $f_{\text{mod}}$, we found another strong response to the applied excitation besides the RF modulation at the instability frequency. Close to the 3rd harmonic of the synchrotron frequency $f_s$, the excitation has an even stronger effect on the fluctuation of the CSR power signal. This is caused by a new set of micro-structures (see Fig. 4) imprinted on the bunch by the applied modulation. The maximum amplitude of the structure is more than three times the amplitude observed due to the

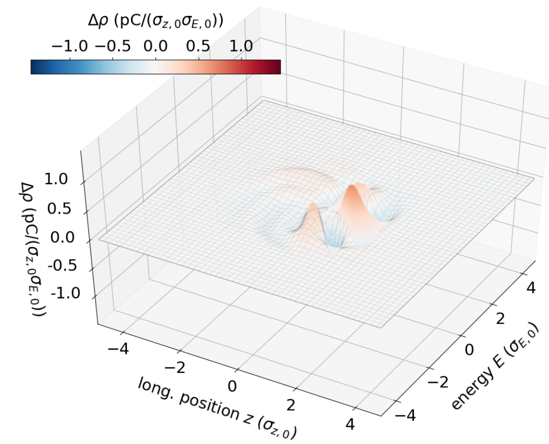


Figure 3: An excitation of the longitudinal dynamics at the instability frequency ($f_{\text{mod}} = f_{\text{inst}}$) leads to an amplification of the already naturally occurring micro-structures by nearly 50 percent.

natural dynamics of the micro-bunching instability in Fig. 1. While the overall shape of a single structure is still similar, the number of micro-structures visible in the longitudinal phase space is reduced from five or six in Fig. 1 to just three in Fig. 4.

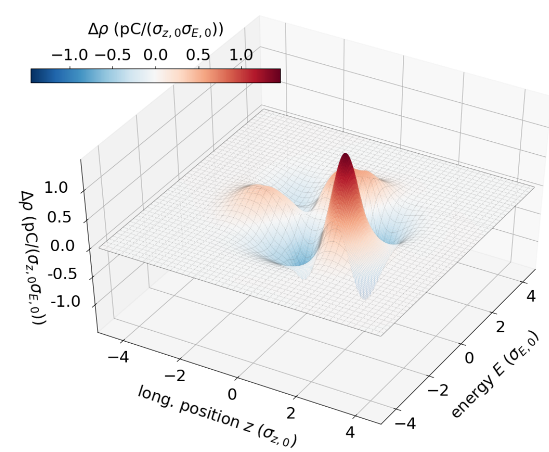


Figure 4: An excitation near the 3rd harmonic of the synchrotron frequency ($f_{\text{mod}} = 3.06 f_s$) leads to the formation of a new set of micro-structures with significantly larger amplitude (compare to Figs. 1 and 3).

## ANALYSIS OF CSR SPECTRUM

In order to assess potential use cases for the illustrated dynamics, we consider the average emitted CSR power under the influence of these RF amplitude modulations. Figure 5 thus displays the average CSR spectrum across a frequency range from 1 GHz to 250 GHz, which corresponds to the

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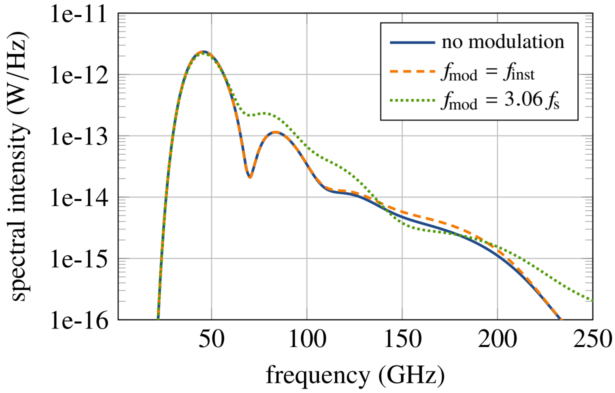


Figure 5: The applied RF amplitude modulations increase the average CSR intensity emitted at frequency ranges corresponding to the spatial extent of the occurring micro-structures.

spatial extent of the observed micro-structures. Compared to the emission of CSR without external excitation, the RF modulation at the instability frequency leads only to small changes in the average emitted spectrum. While the overall distribution of the emitted power is largely unaffected, the intensity between 110 GHz and 220 GHz is notably increased (up to 30 percent) by the applied RF modulation. The excitation near the 3rd harmonic, however, alters the emitted spectrum substantially. As the naturally occurring micro-structures are replaced by a new set of structures imprinted on the beam, the emitted power at frequencies corresponding to the spatial extent of the original structure (around 160 GHz) is visibly reduced. The CSR emission between 60 GHz and 140 GHz on the other hand is increased by a large margin, even up to a full order of magnitude. This is due to the large amplitude and increased spatial extent of the micro-structures depicted in Fig. 4. The considered example would thus be of particular interest for experiments with a requirement of intense CSR in the frequency range around 100 GHz. However, the question at which frequencies and to what extent new structures can be imprinted on the beam is still under investigation. As the shape of the structure directly determines the spectral distribution of the CSR emission, it may be possible to cover further frequency ranges with this approach. We consider this a promising subject of further research, in particular, as it may also yield additional insights on why the naturally occurring structure forms in the first place.

## VERIFICATION IN EXPERIMENTS

The excitation of micro-bunching dynamics via RF amplitude modulation discussed above was tested in first experiments at the KIT storage ring KARA.

For this purpose, the accelerator was operated in short-bunch mode to induce the micro-bunching instability while observing the emitted CSR with a broad-band THz detector (see e.g. [9]). The natural instability frequency $f_{inst}$ was extracted from these measurement and used to determine the modulation frequency $f_{mod}$. As a direct comparison of the measured CSR power signals is quite challenging in the time domain due to various sources of noise, we consider the Fourier-transformed signals instead. Figure 6 illustrates the distinct effect of the applied RF amplitude modulation on the micro-bunching dynamics. The spectral contribution of the instability frequency is enlarged by a factor of about five, which directly corresponds to an increased oscillation amplitude (as in Fig. 2) and suggests a similar amplification of the naturally occurring micro-structures as depicted in Fig. 3.

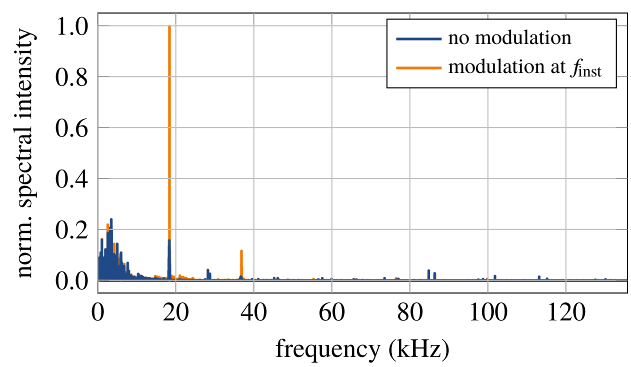


Figure 6: The Fourier-transformed, measured CSR power signals indicate an excitation of the micro-bunching dynamics driven by the applied RF amplitude modulation ($f_{inst}$ = 18.45 kHz, amplitude of five percent).

## SUMMARY AND OUTLOOK

We demonstrated how an RF amplitude modulation can drive the micro-bunching dynamics in short electron bunches, including the possibility to imprint a new set of micro-structures on the beam. This effect can be used to increase the emission of CSR at frequency ranges corresponding to the spatial extent of the occurring structures.

Besides more extensive simulation studies to further explore this option, the effect should be confirmed more clearly in measurements. This can e.g. be achieved by probing different parts of the CSR spectrum through narrow-band THz detectors as described in [10] or by direct observation of the micro-structures with an electro-optical near-field setup [11]. For the overarching objective of full control over the micro-bunching dynamics, we also explore machine learning algorithms [12] to be implemented directly on hardware [13].

## ACKNOWLEDGEMENT

T. Boltz, E. Blomley and P. Schreiber acknowledge the support by the DFG-funded Doctoral School "Karlsruhe School of Elementary Particle and Astroparticle Physics: Science and Technology (KSETA)". This work is supported by the BMBF project 05K19VKC TiMo (Federal Ministry of Education and Research).

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