MICROBUNCHING THRESHOLD MANIPULATION BY A CORRUGATED STRUCTURE IMPEDANCE AT KARA

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Abstract

Two parallel corrugated plates can be used to manipulate the impedance of an electron storage ring such as the KIT storage ring KARA (KArlsruhe Research Accelerator). This impedance manipulation structure opens up the possibility to eventually control the electron beam dynamics and the emitted coherent synchrotron radiation (CSR). In this contribution, we present the impedance that is most effective in manipulating the threshold of the microbunching instability for different machine settings. Furthermore, we show how the resonance frequency of this impedance is related to the spectrum of the substructures in the electron bunches.

INTRODUCTION

There is an ever-increasing demand of brilliance and photon flux at synchrotron light sources. Longitudinal coherence of the photon pulse can be achieved by temporal compression of the electron bunch. Then, the bunches emit coherent synchrotron radiation (CSR), whose intensity is enhanced by several orders of magnitude compared to incoherent radiation. To extend the CSR to the THz frequency range, the electron bunch length is reduced to the single-digit picosecond (ps) time scale.

At the KARA storage ring, the longitudinal compression is realized with dedicated magnet optics reducing the momentum compaction factor, which is also referred to as low-α_C mode [1,2]. The high particle density causes non-linear phenomena like the micro-bunching instability. This instability occurs due to the interaction of the bunches with their self-emitted CSR. This leads to longitudinal deformations and forms substructures imprinted on the longitudinal bunch profile, and dynamical fluctuations, which cause quasi-periodic outbursts [1,3,4]. On the other hand, the current range with temporal stable substructures without the outbursts can be used as a source of intense THz radiation. Consequently, the outbursts must be controlled to reach higher brilliance and to open the THz frequency range for applications at synchrotron light sources.

For this purpose, a versatile impedance manipulation chamber is currently being designed for the KARA storage ring to manipulate the longitudinal beam dynamics of the electron bunches by the additionally created impedance and wake field. A pair of horizontal parallel plates with periodic rectangular corrugations creates the additional geometric impedance. A schematic cross-section of the corrugated plates is shown in Figure 1 with the corrugation depth h, the periodic length L, and the longitudinal gap g. To our knowledge, such structures are so far only installed as energy dechirpers in FELs - like PAL-XFEL [5] and SwissFEL [6] - but have not been installed in a storage ring, where the bunches are periodically affected by the corrugated plate impedance. The impedance can be described by a broad-band resonator [7]

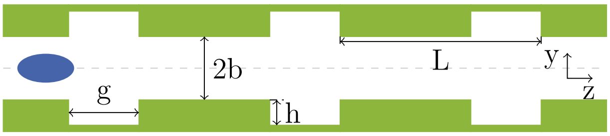

Figure 1: Corrugated plates in cross-section with the relevant geometric parameters. The blue ellipse indicates an electron bunch. Not to scale.

$$Z^{\parallel}(f) = \frac{Z_0}{1 + iQ\left(\frac{f_{\text{res}}}{f} - \frac{f}{f_{\text{res}}}\right)}, \qquad (1)$$

which is characterized by its resonance frequency f_{res}, shunt impedance Z_0, and quality factor Q. The systematic simulation studies of the impedance - presented in [8] - show that for $50\,\text{GHz} \leq f_{\text{res}} \leq 200\,\text{GHz}$, the corrugation dimensions are in the order of $100\,\mu\text{m}$ and that a structure with $Z_0 = 1\,\text{k}\Omega$ and $Q = 3$ can be realized for the available space at the KARA storage ring.

The longitudinal beam dynamics simulations [9] with the KIT in-house developed Vlasov-Fokker-Planck solver Inovesa [10] reveal that the impedance resonance frequency is the defining parameter, how the beam dynamics and the micro-bunching instability parameters are affected. By the correct choice of f_{res}, either the dominant fluctuation frequency of the CSR emission can be changed, or the bursting threshold can be reduced so that intense THz radiation is emitted for lower bunch currents.

This contribution focuses on the impedances that manipulate the bursting threshold effectively. The dependence on the KARA machine and beam settings gives insights into the underlying and driving mechanisms of the micro-bunching instability and the creation of the substructures in the longitudinal bunch profile.

MOST EFFECTIVE IMPEDANCE

The most effective impedance resonance frequency $\hat{f}_{\text{res}}$ to manipulate the micro-bunching bursting threshold I_{thr} is defined as the frequency f_{res}, which causes the strongest CSR fluctuation power 1.5% below the unperturbed bursting threshold I_{thr}. In this context, the unperturbed case means the settings without an additional corrugated plate impedance. In [11], we have already discussed that $\hat{f}_{\text{res}}$ has a sawtooth-

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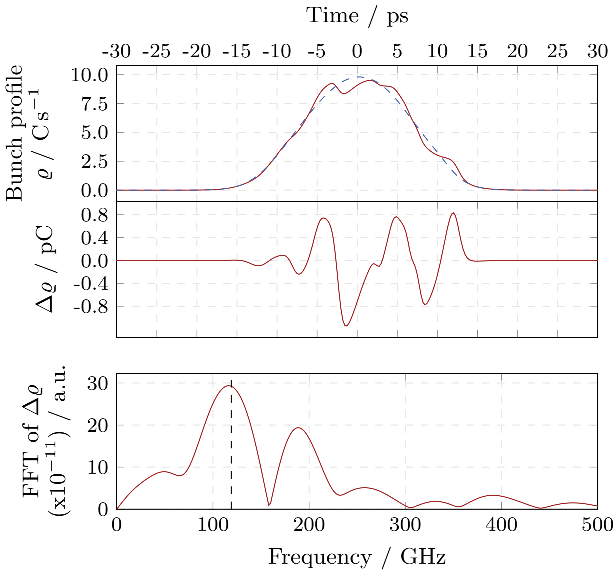


Figure 2: Top: Simulated bunch profile (red line) at the time step with the largest CSR emission power and the temporal averaged bunch profile (dashed blue line) as reference. Below: The substructures in the longitudinal bunch profile become more visible after subtracting the temporal average profile. Bottom: The Fourier transform of this relative bunch profile $\Delta\varrho$ indicates the dominant frequency of its spectrum, which is in good agreement with $\hat{f}_{\mathrm{res}}$ (dashed black line).

like dependency on the zero-current bunch length and remains in the range 83 GHz to 133 GHz for all investigated machine settings in the low-α_{C} operation mode at KARA. The periodicity of this sawtooth corresponds to the number of substructures N that arise in the longitudinal phase space and are imprinted on the longitudinal bunch profile.

This gives a strong indication that the dimensions of the substructures directly affect the most effective impedance to enhance the creation of these substructures so that they are investigated more in detail. To compare the substructures with the impedance resonance frequency, the spectra of the substructures for the unperturbed settings are studied. The top part of Figure 2 shows the bunch profile with the substructures as an example in the range of the current, where the outbursts are most intense. Subtracting the profile from the temporal average and nearly Gaussian bunch shape (dashed blue line) makes the imprinted substructures more visible (shown underneath). There, it can be seen that the amplitude of the substructures is in the order of a few percent and that they consist of a positive and negative deviations from the time-averaged profile. In the plot at the bottom, the Fourier transform of the deviation $\Delta\varrho$ is shown. Note that the spectrum of the substructure can be characterized by a dominant frequency f_{sub}. This frequency is a measure of the size and periodicity of the substructures. However, this dominant substructure frequency correlates to the bunch length σ. The vertical dashed line – representing $\hat{f}_{\mathrm{res}}$ of this setting – matches this bunch spectrum frequency in the bursting regime of the micro-bunching instability very well.

CURRENT SCAN

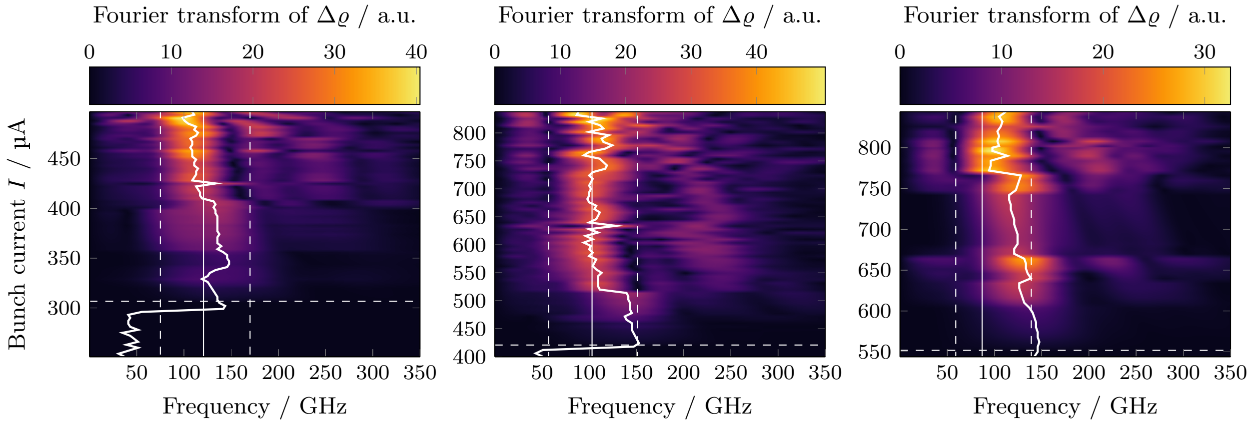
For a better understanding of and insight into the driving mechanism of the micro-bunching instability, the bunch spectrum as a function of the beam current is investigated for different KARA machine settings. To identify the already existing substructures whose creation is enhanced by an additional impedance, the scans are simulated for the unperturbed settings with only the existing CSR impedance. These current scans are shown for three machine settings – defined by the acceleration voltage V_{acc} and momentum compaction factor α_{C} – in Figure 3. For each current step, the substructure spectrum of the simulation time step with the strongest manifestation of the substructures and, consequently, the highest CSR emission is used for the spectrogram.

Below I_{thr}, the bunch profile does not have imprinted substructures and is stable over time. Therefore, no significant dominant substructure frequency arises in this current range. Above this threshold current, the substructures occur and increase in amplitude with increasing beam current. In the Fourier transform of $\Delta\varrho$, this can be seen by the fact that a dominant frequency range around the respective f_{sub} occurs whose color changes from red to yellow. This bright and dominant frequency range in the substructure bunch spectra above I_{thr} remains mainly in the range between the dashed vertical lines of the effective impedance resonance frequencies. The decrease can be explained by the increased bunch length with larger beam currents due to the potential well distortion. Consequently, the size of the substructures increases, too, and its dominant frequency decreases. The number of substructures is constant and independent of the beam current for a dedicated machine setting. Consequently, the size of the substructures increases with the bunch current as well, so that the dominant substructure frequency decreases.

The creation of the substructures and the resulting emission of enhanced THz radiation can be extended to lower beam currents by an additional impedance source. The study of the Fourier transform of $\Delta\varrho$ has shown that the resonance frequency of the most effective impedance ($\hat{f}_{\mathrm{res}}$) to trigger the creation of the substructures matches the dominant substructure frequency f_{sub}, which determines the size of the substructures in the beam current regime of the micro-bunching instability. In the time domain, this means that the periodicity of the wake function needs to match the size of the substructures directly in the longitudinal bunch profile to cause the enhancement of substructures and their CSR emission.

OUTLOOK

The implication of an installation of a pair of corrugated plates into the KARA storage ring to manipulate the longitudinal impedance of the storage ring to affect the properties of the micro-bunching instability is presented. Because the



(a) $\alpha_c = 0.6 \times 10^{-3}$, $V_{acc} = 0.8\,\text{MV}$ (b) $\alpha_c = 0.8 \times 10^{-3}$, $V_{acc} = 0.9\,\text{MV}$ (c) $\alpha_c = 1.0 \times 10^{-3}$, $V_{acc} = 1.0\,\text{MV}$

Figure 3: The spectra of the relative substructure bunch profiles $\Delta\varrho$ are shown as a function of the beam current for different machine settings. The vertical solid straight white line represents the most effective impedance resonance frequency $\hat{f}_{res}$. The horizontal dashed line marks the threshold current – according to the machine settings and increasing with the zero-current bunch length – of the micro-bunching instability, above which the substructures are created, and intense THz radiation is emitted. Furthermore, the vertical solid line marks $\hat{f}_{res}$, and the dashed vertical lines represent the minimal and maximal impedance resonance frequencies that cause enhanced CSR below the unperturbed bursting threshold current, respectively. The solid white curve marks the dominant substructure frequency f_{sub} as a function of the current.

bursting threshold and, therefore, the emission of intense CSR, can be lowered by a corrugated structure whose periodicity of the wake function matches the longitudinal size of the substructures, the impedance resonance frequency is chosen accordingly. For the first structure, the resonance frequency is set to $f_{res} = 110\,\text{GHz}$, which is equal to $\hat{f}_{res}$ of the best studied KARA low-α_C setting [12].

The installation of an additional corrugated structure cannot suppress the instability completely because the geometric impedance is increased. To reduce or completely avoid the creation of longitudinal substructures, the impact of reducing the impedance in the frequency range around f_{sub} needs to be first examined in simulation studies. Based on that, it might be possible to reduce the geometric impedances in the relevant frequency range, allowing higher bunch charges in high-brilliance light sources.

ACKNOWLEDGEMENTS

This work is supported by the DFG project 431704792 in the ANR-DFG collaboration project ULTRASYNC.

S. Maier acknowledges the support by the Doctoral School "Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology“ (KSETA).

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