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INCREASING THE SINGLE-BUNCH INSTABILITY THRESHOLD BY BUNCH SPLITTING DUE TO RF PHASE MODULATION

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Abstract

RF phase modulation at twice the synchrotron frequency can be used to split a stored electron bunch into two or more bunchlets orbiting each other. We report on time-resolved measurements at the Karlsruhe Research Accelerator (KARA), where this bunch splitting was used to increase the threshold current of the microbunching instability, happening in the short-bunch operation mode. Turning the modulation on and off reproducibly affects the sawtooth behavior of the emitted coherent synchrotron radiation.

A significant part of the results was published in Ref. [1, Chapter 6.6]

EFFECT OF RF PHASE MODULATION

The potential well can be influenced by a change of the RF potential. The RF phase is controlled by the LLRF system, which is capable of performing various modulations. Periodic changes lead to a nonlinear phase space and were studied intensively in the early 1990s [2–5]. It was shown, that a constant phase modulation of the RF can lead to several stable operation points, called *islands of stability* [6]. All stable islands get populated by electrons, leading to several small bunches, called *bunchlets*. RF modulations were and are used in several accelerators to increase the bunch length [7], to increase the beam life time [8, 9], or to damp instabilities [10].

To study the effect of such an RF phase modulation on the microbunching instability (MBI), we modulate the phase with twice the synchrotron frequency as described in [11] by the LLRF system [12]. Without modulation, all electrons are gathered in a single island. The frequency f_m/Hz and amplitude A_m/rad of the sinusoidal modulation define the number of islands during the excitation [11]

$$\frac{f_m}{f_s} > \left(2 - \frac{A_m}{2}\tan(\pi - \psi_0)\right) \longmapsto 2 \text{ islands}, \quad (1)$$

$$\frac{f_m}{f_s} < \left(2 - \frac{A_m}{2}\tan(\pi - \psi_0)\right) \longmapsto 3 \text{ islands}. \quad (2)$$

In the following experiment, $f_m/f_s = 2$ is chosen with a phase modulation amplitude of two degrees, which ensures a two-island operation. With the 500 MHz RF system, this corresponds to a periodical shift of the RF potential by 11.1 ps. The machine parameters are summarized in Table 1.

Table 1: Machine Parameters During RF Phase Modulation

Beam energy	E	1.287 GeV
Bunch current	I_b	0.38 mA
RF amplitude	V_{RF}	755 kV
Synchrotron frequency	f_s	7.5 kHz
Modulation frequency	f_m	15 kHz
Modulation amplitude	A_m	0.035 rad
Synchronous phase	ψ_0	3.121 rad
Calc. MBI threshold	$I_{b,th}$	0.2 mA
Calc. momentum compaction	α_c	4.8×10^{-4}
Calc. zero-current bunch length	$\sigma_{z,0}$	4.6 ps
Avg unmodulated bunch length	$\sigma_{z,t}$	17(2) ps

Longitudinal bunch profile measurements made with a streak camera are shown in Fig. 1. In this sawtooth bursting regime, the unmodulated bunch shows a measured average RMS length of (16.5 ± 1.7) ps due to bunch-lengthening. Here, the bunch hardly performs any coherent synchrotron motion. However, when applying a 2fs-modulation, two bunchlets are observed, performing large amplitude oscillations around the former stable phase.

In order to analyze the effect of the modulation in the THz signal, two measurements were set up. The first measurement was performed in the IR1 beamline: An optical APD and a small-band Schottky-Barrier-Diode (SBD) sensitive between 140 GHz to 220 GHz were read out synchronously by an oscilloscope in segmented mode. The second measurement was carried out at the IR2 beamline, where a broadband THz detector was read out by KAPTURE [13–15]. The two experiments were synchronized, so that the same bunch could be observed for the same turns. Both readout devices were triggered by a common trigger. While the oscilloscope readout is limited to 18 ms. The LLRF system, activating the phase modulation was triggered 1 ms after the measurement devices. With this synchronized set up, it is possible to observe the effect on different detectors at different positions at the same time. The APD is sensitive to the optical range and therefore only to incoherent synchrotron radiation, while the THz detectors are sensitive to emitted coherent synchrotron radiation.

MEASUREMENTS

In the experiment, the modulation is turned on and off repeatedly by the LLRF system. Figure 2 shows the pulse amplitude of the broadband detector measured at the IR2 beamline by KAPTURE. After the modulation is turned on, a burst, lasting approximately 7 ms with high frequency oscillation, follows. Afterwards, the amplitude drops to almost zero before it recovers to a nearly stable, but comparably low

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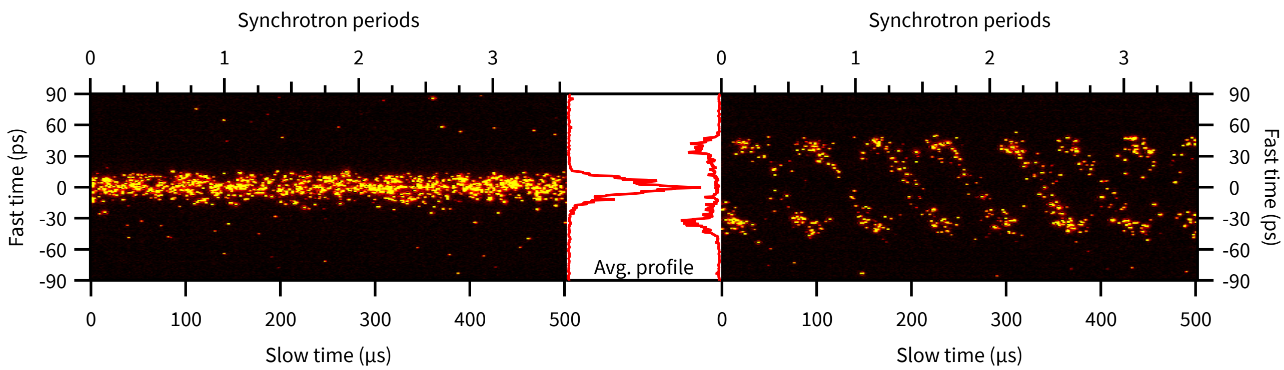

Figure 1: Streak camera measurements of a stable (left) and a modulated (right) single bunch. In the case of a modulated beam, two bunchlets can be seen, oscillating with almost the stable synchrotron oscillation frequency around the center. The peak-to-peak amplitude of the oscillation is around 70 ps while the phase modulation is 2° (11.1 ps). Due to dispersion, the two bunchlets also orbit each other in the horizontal plane, leading to periodic out-of-focus images of reduced intensity. The single random light spots are artifacts of the measurement: single stray photons detected by the fluorescence screen.

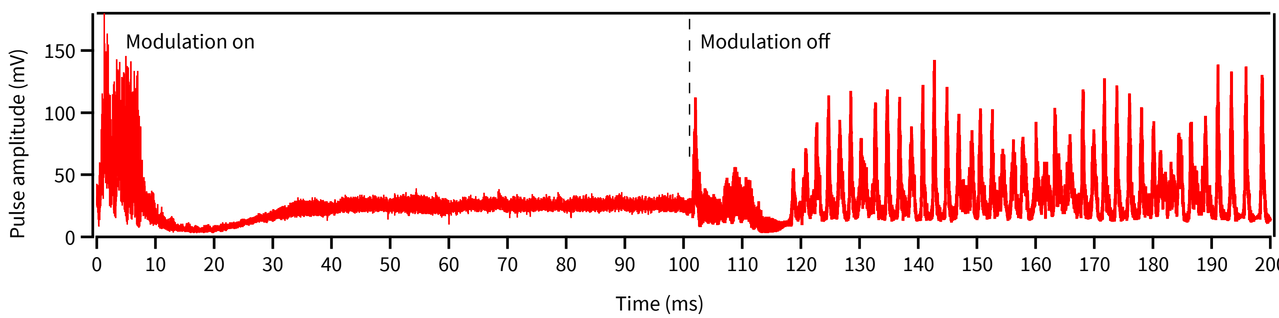

Figure 2: Influence of 2fs RF phase modulation on the bursting behavior. Pulse amplitude of a broadband THz detector read out by KAPTURE. The modulation is turned on 1 ms after the start of the measurement and turned off 100 ms later. The width of the line is caused by high frequency oscillations, which cannot be resolved in the shown time scale.

intensity. However, the intensity is still orders of magnitude higher than the incoherent radiation. When turning off the modulation, a short burst is emitted shortly after, followed by some modulation and a small region of low intensity, before the normal bursting behavior restarts at around 20 ms after switching off the modulation.

The spectra of the emitted pulse amplitudes between 40 ms to 100 ms and 140 ms to 200 ms are shown in Fig. 3. Without modulation, the observed spectrum is the expected spectrum of the MBI for that bunch current. After applying the 2fs-modulation, the characteristic bursting frequencies are gone and the spectrum mainly consists of two frequencies and their harmonics. As the synchrotron frequency was 7.5 kHz, a 15 kHz modulation was applied. This modulation frequency and its harmonics are very prominent in the spectrum. Although the modulated spectrum looks stable, despite of the modulation frequency, one can not directly conclude, that the modulation directly suppresses the MBI. One has to keep in mind, that each of the created bunchlets has only half of the initial bunch current and therefore, in the observed case, the bunchlet current is below the MBI threshold of 0.2 mA. Consequently, splitting the bunch in two bunchlets effectively doubles the threshold bunch current of the instability.

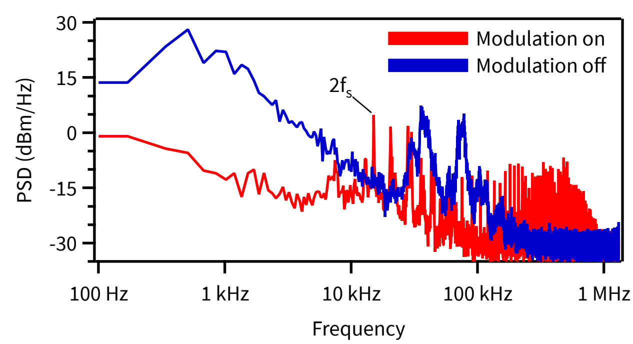

Figure 3: Spectra of the pulse amplitude evolution with (red) and without (blue) modulation. The spectra were calculated by a FFT for the time ranges 40 ms to 100 ms and 140 ms to 200 ms of Fig. 2.

The transition from the modulated to the unmodulated signal and vice versa described above changes with bunch current. But nevertheless, it is reproducible for a given current. Figure 4 shows three measured transitions from the unmodulated to the modulated state (left) and back (right), the time between the measurements being 20 s. Here, the data is taken at the IR1 beamline with the small-band detector, sensitive between 140 GHz to 220 GHz. Due to the

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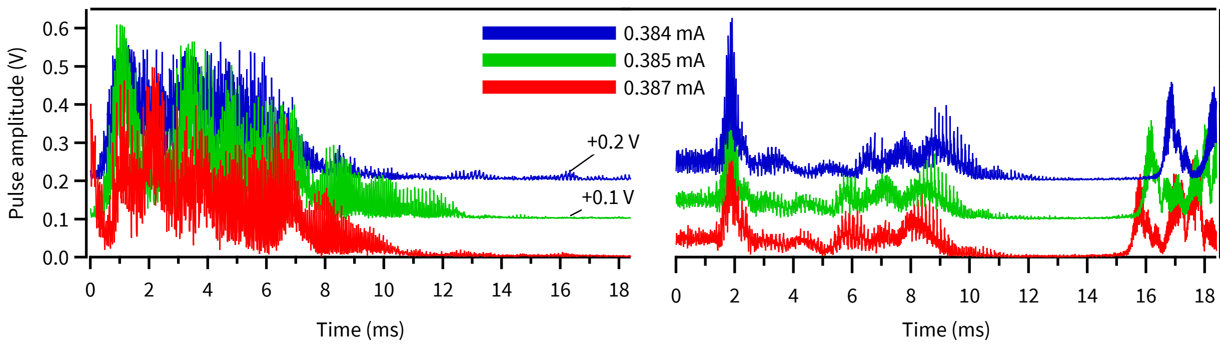

Figure 4: Pulse amplitude evolution of a narrowband SBD detector after a 2fs-modulation is applied. The time difference between the measurements is 20 s, so that the bunch current has only slightly decreased. The response to the onset of the modulation (left) is similar in all measurements, independent of the bursting phase the bunch had before. The response is therefore triggered by the onset of the modulation. The visible saturation of the pulse amplitude during the outburst is due to the oscilloscope's limitation in dynamic range. The response to switching off the modulation (right) is also similar in each case. After a small phase of reduced emission, the typical bursting behavior restarts after approximately 16 ms.

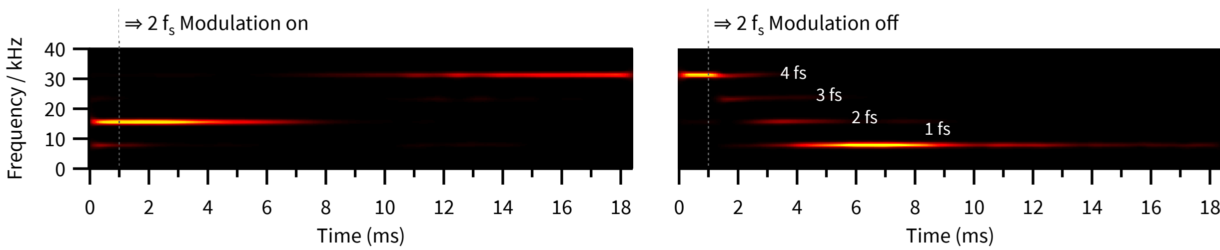

Figure 5: Wigner transform of the APD amplitude evolution. Due to an aperture, the APD amplitude is sensitive to the bunch position. Without modulation, only the synchrotron frequency is seen. When switching the modulation on, a strong 2fs line is seen for a short time, then 4fs becomes dominant.

limited memory of the oscilloscope, only about 18 ms could be observed at once, but the behavior is quite similar to the KAPTURE measurement in Fig. 2 which shows the long time scales, taking into account the different frequency response of the detectors. This also shows, that the effect is not a local phenomenon (like due to orbit bumps) at the IR2 beamline but is also observed in the ring later on.

The modulation, starting after 1 ms, leads to high frequency oscillations of the THz amplitude for all observed cases, independent of the bursting phase the bunch had before. After 10 ms, which coincides with the longitudinal damping time τ_d, the THz radiation has almost ceased. The increase afterwards as seen in Fig. 2 happens after 20 ms. The other case, the transition from modulated to unmodulated, is shown on the right. At around 2 ms, the THz radiation has an outburst, followed by a characteristic tail until the radiation almost vanishes around 12 ms. Approximately 6 ms after the radiation vanished, the bursting starts again, where the MBI leads to the expected outbursts. The installed APD is only sensitive in the visible range and therefore only measures the stable incoherent radiation. However, due to a small aperture in the beam path, the diode signal is sensitive to positional changes of the source point and shows the bunch movement. The instantaneous modulation frequencies evaluated by a Wigner transform of the APD signal are shown in Fig. 5 for the same time ranges as before.

SUMMARY

Phase modulation at twice the synchrotron frequency results in electron bunch splitting and allows the charge of the individual bunchlets to be pushed below the instability threshold. Effectively, the bunch-current could be doubled before the instability occurs. We have shown how we can use the phase modulation as a switch to turn on and off the micro-bunching instability when the bunch current is below two times the threshold current. The transients are quite reproducible and could be used in the future to induce the emission of powerful THz radiation. Efforts are already underway to improve the THz radiation by machine learning techniques [16].

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