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PILE-UP EFFECT OF COLD BUTTON BPMS IN THE EUROPEAN XFEL ACCELERATOR

D. Lipka*, B. Lorbeer, DESY, Hamburg, Germany

Abstract

The European XFEL facility is in operation with a maximum of 2700 bunches in one train. The highest bunch repetition rate is 4.5 MHz; this corresponds to a minimum time separation of 222 ns. The measurement of the beam properties for each bunch in a train is required. Therefore the beam position monitor (BPM) system needs to separate the signals from each bunch. All BPM types (button, re-entrant and cavity) fulfill this requirement except a few button BPMs installed inside of the cold accelerator module, where Pile-Up from the train can be observed. To identify the cause of this effect we measured the S-parameters during a shutdown of the accelerator, compared it with a similar BPM at the FLASH accelerator but located in a warm section and finally measured the spectrum of the button signal during beam operation. As a result, resonances were found at about 2.46 GHz with relatively high quality factor that remains within the frequency range accepted by the electronics.

INTRODUCTION

The European XFEL is a user facility generating X-rays in trains with a 222 ns (4.5 MHz) minimum separation [1]. The maximum length of one train is 600 µs repeat at 10 Hz resulting in a maximum of 2700 bunches per train with energies between 8 and 17.5 GeV [2]. Individual bunches in one train can be redirected to two different beamlines, called the Northern and Southern branch. The Northern branch contains two SASE undulator sections, SASE1 for hard and SASE3 for soft X-rays. Different parts of the train are used to generate the SASE effect in both undulator sections by initiating a betatron oscillation via fast kickers. The Southern branch contains a second hard X-ray undulator section. To be able to control and direct the individual bunches in one train, each bunch position needs to be measured with the Beam Position Monitor (BPM) system [3].

The electron bunches are accelerated by superconducting cavities installed in 98 cryogenic modules. Each module contains 8 cavities followed by a cold quadrupole, a BPM and a higher-order-mode absorber [4] (see Figures 1 and 2). The accelerator is divided into 3 cryogenic sections, where the longest is about 1 km. Therefore the electron beam diagnostics of the accelerator sections relies mainly on the BPMs, along with beam loss monitors outside the modules.

The BPMs of the 98 cryogenic modules, 74 have wide-band button type [5], in the other 24 modules re-entrant cavity BPMs installed as an in-kind contribution from CEA Saclay [6]. All BPMs are cryogenically tested to be vacuum tight before installation in the modules. Up to now no degradation of the vacuum has been seen from these devices. But during 4.5 MHz operation about 17 button BPMs showed an unexpected beam charge distribution (see Figure 3). This effect, and the investigations to understand and overcome it, are described in the following.

* Dirk.Lipka@desy.de

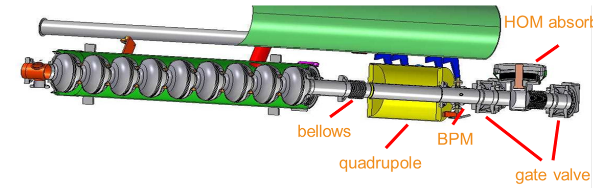

Figure 1: Schematic arrangement of components at the end of a cryogenic module. Beam direction is from left to right.

Figure 2: Photo of components at the end of a cryogenic module before installation; from right: housing of the cavity, housing of the quadrupole, button BPM.

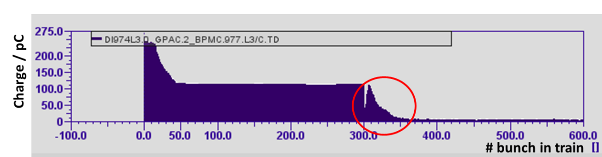

Figure 3: Beam charge reading of a train with 300 bunches. After the 300th bunch the reading indicates a signal which is non-zero.

PILE-UP

The button BPM system consists of the monitor inside the module, Radio Frequency (RF) cables and BPM read-out electronics. The read-out electronics are composed of analog Front-End electronics and digital electronics for data processing. The housing is a so called Modular BPM Unit (MBU) [7]. The 3-dB bandwidth of the analog Front-End electronics is between 1.53 and 2.28 GHz; the lower limit

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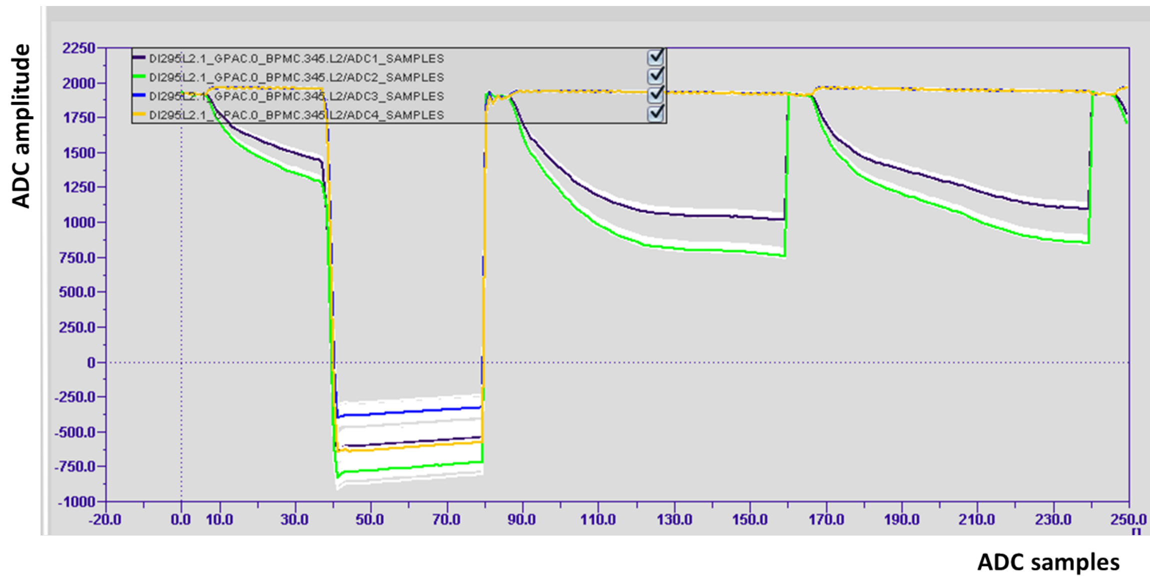

Figure 4: ADC waveform of 3 beam buckets with an ADC repetition rate of 433.3 MHz. The blue and yellow lines are for the horizontal buttons, the black and green lines are for the vertical buttons. Due to 1.1 MHz operation the 2. and 3. buckets are empty; only the effect due to the Pile-Up is generating an additional negative amplitude for the vertical channels. A discharge signal at ADC sample points n times 80 (n an integer) results in the baseline ADC amplitude.

is chosen to avoid picking up signals from the accelerator cavity at 1.3 GHz [8]. To exclude the possibility that the electronics caused the effect due to internal crosstalk, the cables of two monitors were swapped before the Front-End. This measurement showed that the effect moved with the monitor to the other electronics. Therefore the source is within the monitor.

In order to understand the Pile-Up effect after the last bunch in a bunch train the ADC raw data has been investigated (Figure 4). The ADC baseline level lies at around 1950 (12 bit ADC with range between ±2048). The two pick-up signals in the horizontal plane show a characteristic as expected (blue and yellow waveform). The signals from the vertical pick-ups deliver some artefacts from sample zero to 40 and after sample 75 (green and black waveform). These signals are misinterpreted as bunches and deliver position and charge data in an actually empty bucket. It is expected that the calculated charges and positions for the filled bunch buckets are affected too.

The following investigation monitored the dependency of the Pile-Up on the bunch charge and position. The ADC values for an empty bunch bucket is correlated with the bunch property (see Figure 5). Without the Pile-Up effect the baseline ADC amplitude at about 1950 should be visible, but in this example the ADC amplitude for the vertical channel shows a decrease of amplitude with charge. The different steps are caused by different attenuators in the Front-End electronics. No correlation was found between the Pile-Up effect and the beam position. Therefore it is expected that a monopole resonance with a decay constant longer than the bunch separation causes the Pile-Up.

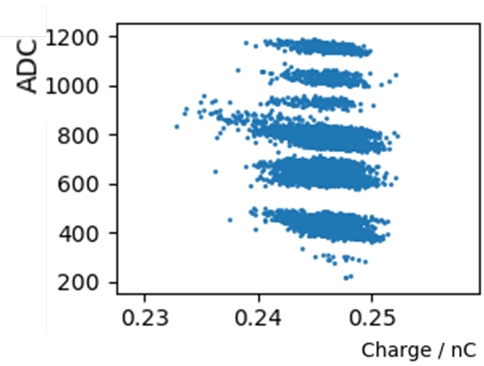

Figure 5: ADC amplitude as a function of beam charge of the first bunch with an empty bucket at the sample point 150 (see Figure 4). The steps are caused by different Front-End attenuators.

In the next investigation the resonances of the button BPM itself in the cryogenic module (at cryogenic temperatures) have been measured with a network analyzer while the beam and acceleration RF power was off. The corresponding transmission S-parameters of two opposite buttons are shown in Figure 6. The spectrum up to 2 GHz is not shown because no visible resonances have been measured, the relevant spectrum has been found between 2 and 3 GHz. Several resonances are visible for the cold BPMC compared to a warm button BPMA with smaller beam pipe diameter. While the warm BPMA shows no resonance in this frequency range, all resonances of the cold BPMs result in quality factors between 57 and 106. The corresponding time constants of these resonances are too short to cause the Pile-Up ef-

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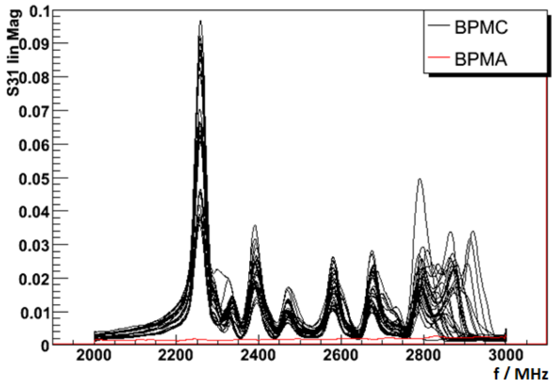

Figure 6: Transmission spectrum measured with a network analyzer of several cold button BPMs (BPMC) between 2 and 3 GHz in comparison with a warm standard BPMA.

fect. The spectrum is in agreement with an identical warm prototype at the FLASH facility, except for an additional resonance at (2471.2 ± 3.6) MHz in the cold BPM (but the time constant of this resonance is too short).

To investigate the additional resonance, a spectrum analyzer has been installed in one rack to measure the signals during beam operation (see Figure 7). The single input port

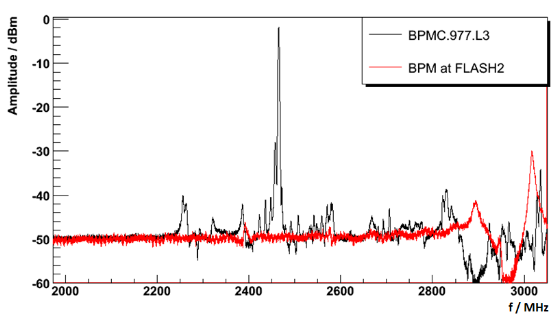

Figure 7: Spectrum of one cold and the warm prototype at FLASH during beam operation between 2 and 3 GHz.

of the spectrum analyzer has been connected to different buttons with and without Pile-Up effect. The spectrum up to 2 GHz did not show any resonance; especially at the accelerator RF frequency of 1.3 GHz during operation. Also here the relevant spectrum during beam operation has been found between 2 and 3 GHz. The spectrum have been compared with a warm prototype button BPM at FLASH. The identified resonances at 2457.1 MHz and 2464.7 MHz have quality factors of 945 and 1232 respectively which results in decay times of 122 and 159 ns and strong amplitudes of −28 and −2 dBm instead of −50 dBm at FLASH. This is the cause of the Pile-Up effect. Other connected BPM channels show similar resonances and quality factors, with frequencies differing by about 2 MHz.

Since the resonances can not be produced by the BPM itself, other sources should be considered. From the beam measurements above, one can conclude that a TM_{01} mode will cause these resonances. From [9], several modes (monopole, dipole, quadrupole and sextopole) are expected in this frequency range from the neighboring accelerator cavity, but with a cut-off frequency at 3 GHz. Therefore the measured resonances should be caused by a monopole mode generated through the beam propagation itself in the accelerator cavity and transmitted to the BPM. Measurements with a network analyzer of the cavity next to the BPM under investigation with the higher-order-mode absorber showed resonance frequencies [10] which agree to the here shown spectrum analyzer frequency results, indicated in Figure 7. Different cavities were measured, and it was found that the resonances in this frequency range differ from cavity to cavity by few MHz, and the amplitudes of the resonances are different by about a factor of 10. Therefore due to the differences in the amplitude of the resonances in the accelerator cavities, only few BPM are affected by the Pile-Up effect.

During the above mentioned measurement one BPM with a strong Pile-Up was equipped with low-pass filters: 3 dB attenuation at 1 GHz. This should reduce the amplitude at 2.4 GHz by 25 dB. The button BPM resolution changed from about 4 µm to 12 µm at 250 pC, which is still acceptable. Due to the strong amplitude from the accelerator cavity (see Figure 7) this attenuation reduces the effect but it was still not negligible, because at the resonance frequency the attenuation of the Front-End electronics is only 20 dB. Therefore 2 identical low-pass filters were installed for each channel at one BPM, which reduced the signal at 2.4 GHz by 60 dB. This results in a negligible Pile-Up effect but the resolution of the BPM system increased to 65 µm at 250 pC because of the decreased bunch voltage amplitude, which almost does not fulfill the requirement. Therefore adapted filters are necessary to reduce the Pile-Up effect.

CONCLUSION

A Pile-Up effect is measured with the cold button BPMs in the European XFEL. This is caused by higher-order-modes induced signals from the beam in the adjacent accelerator cavities. To avoid this effect, the electronics bandwidth should be adapted to exclude these resonances.

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REFERENCES

[1] W. Decking *et al.*, "Status of the European XFEL", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 1721–1723. doi:10.18429/JACoW-IPAC2019-TUPRB020

[2] M. Scholz, "FEL Performance Achieved at European XFEL", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Van-

ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-WEAO02

couver, Canada, Apr.-May 2018, pp. 29–33. doi:10.18429/JACoW-IPAC2018-MOZGBD2

[3] D. Lipka, “Very First Experience with the Standard Diagnostics at the European XFEL”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May 2017, pp. 180–183. doi:10.18429/JACoW-IPAC2017-MOPAB043

[4] D. Noelle *et al.*, “BPMs for the XFEL Cryo module”, in *Proc. 8th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC’07)*, Venice, Italy, May 2007, paper TUPB12, pp. 84–86.

[5] D. Lipka, B. Lorbeer, D. Noelle, M. Siemens, and S. Vilcins, “Button BPM Development for the European XFEL”, in *Proc. 10th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC’11)*, Hamburg, Germany, May 2011, paper MOPD19, pp. 83–85.

[6] C. Simon *et al.*, “Design and Beam Test Results of the Reentrant Cavity BPM for the European XFEL”, in *Proc. 5th Int. Beam Instrumentation Conf. (IBIC’16)*, Barcelona, Spain, Sep. 2016, pp. 356–359. doi:10.18429/JACoW-IBIC2016-TUPG17

[7] B. Keil *et al.*, “A Generic BPM Electronics Platform for European XFEL, SwissFEL and SLS”, in *Proc. 1st Int. Beam Instrumentation Conf. (IBIC’12)*, Tsukuba, Japan, Oct. 2012, paper MOCB02, pp. 11–15.

[8] D. M. Treyer *et al.*, “Design and Beam Test Results of Button BPMs for the European XFEL”, in *Proc. 2nd Int. Beam Instrumentation Conf. (IBIC’13)*, Oxford, UK, Sep. 2013, paper WEPC21, pp. 723–726.

[9] C. Liu, W. Ackermann, W. F. O. Müller, and T. Weiland, “Numerical Calculation of Electromagnetic Fields in Acceleration Cavities Under Precise Consideration of Coupler Structures”, in *Proc. 4th Int. Particle Accelerator Conf. (IPAC’13)*, Shanghai, China, May 2013, paper MOPWO007, pp. 897–899.

[10] N. Baboi, T. Hellert, L. Shi, T. Wamsat, R. M. Jones, and N. Y. Joshi, “HOM Characterization for Beam Diagnostics at the European XFEL Injector”, in *Proc. 5th Int. Beam Instrumentation Conf. (IBIC’16)*, Barcelona, Spain, Sep. 2016, pp. 616–619. doi:10.18429/JACoW-IBIC2016-WEPG03