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BUNCH-BY-BUNCH BEAM POSITION MEASUREMENTS AT PETRA III

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Abstract

The PETRA IV project is set to enhance the current PETRA III synchrotron into an ultra-low-emittance source. The reduced emittance will impose stringent requirements on machine stability and operation. In order to cope with these requirements, bunch-by-bunch information is required from some monitor systems. For precise monitoring of beam position and charge, the Libera Digit 500 instrument from Instrumentation Technologies is tested as a readout electronics for BPMs at the existing machine PETRA III. This system features four channels with a 500 MHz sampling rate, synchronized with the accelerator's RF, enabling observation of beam properties with a bunch-by-bunch resolution, thus facilitating a more comprehensive understanding of beam behavior. This contribution provides an overview of the latest beam measurements at the single bunch level, allowing observation of beam oscillations and injection dynamics.

INTRODUCTION

The 6 GeV synchrotron light source PETRA III [1] at DESY (Hamburg, Germany) has been in user operation since 2010. It features a circumference of 2304 m, its harmonic number is 3840, and it operates with RF frequency of 500 MHz. In the coming years, PETRA III is planned to be turned into an ultra-low-emittance fourth-generation source, PETRA IV. The small beam emittances result in significantly smaller beam sizes, about 7 µm horizontally and 3 µm vertically [2]. To meet these requirements, and get more information on beam oscillations over each turn, bunch-by-bunch information can be essential. For this reason, the Libera Digit500 was installed as the readout electronics for one of PETRA III's BPMs. The time-dependent signals to be analyzed are the $SUM = A+B+C+D$, $X = K_x \frac{(B+C)-(A+D)}{SUM}$ and $Y = K_y \frac{(A+B)-(C+D)}{SUM}$, by their Power Spectral Density (PSD(ω)):

$$\mathrm{PSD}(\omega) = \lim_{T\to\infty} \frac{1}{T}|u(\omega)|^2, \qquad (1)$$

where $u(\omega)$ is the Fourier transform of the data measured in the time domain; with $t = n \times t_{sample}$, t_{sample} is the ADC sampling time; and n is an index [0, N], with N the maximum number of samples.

Firstly, the instrument commissioning is conducted, and, the linearity of the RF front end, as well as that of the instruments' internal attenuators is tested.

Then, PETRA III's injection oscillations are studied. Two cases are examined; injecting single bunches in an empty accelerator, and injecting additional intensity to a previously 40 bunch filled machine. This enables to obtain the individual bunches' longitudinal and transverse oscillations resulting from the injection scheme; and any additional impacts on single bunches arising from the injection kickers.

Secondly, a study of the injection and excitation kickers is carried out, analyzing transverse oscillations on individual bunches for the cases of MBFB enabled and disabled. The horizontal and vertical tunes are obtained, along with the decay times, and coupling between the horizontal and vertical orbits for the different scenarios.

Lastly, the intensity dependent tune shift is investigated. For this study, an inhomogeneous 60 bunch filling pattern is implemented into the accelerator, and the vertical excitation kickers are used, with and without the MBFB system. This can help understand the tune dependency with the single bunch current.

READOUT ELECTRONICS: LIBERA DIGIT500

The Libera Digit500 digitizer, a commercial product from the company Instrumentation Technologies [3], is experimentally tested as the readout of a dedicated BPM. A schematic for the functioning of this instrument is shown in Fig. 1. It features four input channels (A,B,C,D), that are connected to the four BPM pickups, and sampled with a 500 MHz sampling rate, and enabling to perform bunch-resolved measurements. Each channel is adjusted in amplitude with a 31 dB software-controlled variable attenuator, and later sampled by an Analog-to-Digital converter (ADC). Sampling is controlled by an external reference signal (Ref), synchronized to the accelerator's Radio Frequency (f_{ADC}) through a Phase Lock Loop (PLL).The data acquisition is triggered by a Trigger signal (T2), and data is stored into a 2 GB ADC buffer. External attenuators are added before the front-end to ensure the signal power coming from the BPM pick-ups stays within the instrument specifications, as well as to test the front-end linearity.

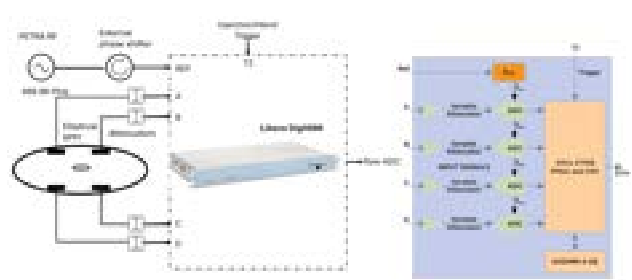

Figure 1: Experimental setup for the bunch-by-bunch measurements, and Libera Digit 500 Dataflow, Image from Instrumentation Technologies [3].

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Instrument Commissioning

DC Offset Compensation The A/D converters and other components in the RF chain exhibit a certain DC offset in the absence of input signals, with varying values for each channel. This offset can be compensated by the instrument itself, where offset values are subtracted from the raw values: $A' = A_{raw}$ - Offs_A. To correctly compensate the offset for each channel, 1024 raw ADC samples are collected at different attenuation levels with no input signals, and offset values are adjusted for each channel to ensure the compensated average equals zero.

Phase Tune Next, the timing adjustment of each of the four ADC converters is adjusted, also known as phase tune. Its calibration is needed to ensure that the four BPM signals have the same phase with respect to the accelerator's RF. To adjust this parameter, the signals' peak values are optimized as a function of the channel phases. Because an external phase shifter is used in the experimental setup, introducing a uniform delay across all channels, the optimal phase tunes are always relative to the setting of this external phase shifter.

Instrument Linearity To investigate the linearity of the instrument, two aspects need to be tested: the RF front-end, and the internal software-controllable variable attenuation before the A/D converters (see Fig. 1). The instrument's internal linearity was tested by plotting the SUM as a function of intensity for different attenuation levels (0-31 dB). As Fig. 2 (a) displays, the fit to a straight line is good, indicating high linearity of the internal attenuation. On the other hand, for the RF front-end linearity test different external attenuation levels were applied to each channel. As shown in Fig. 2 (b), channels with lower attenuation than 40 dB are not entirely linear. However, a 40 dB attenuation strongly reduces the dynamic range of the system, therefore, external attenuation was set to 16 dB, since the main analysis focuses on the frequency domain.

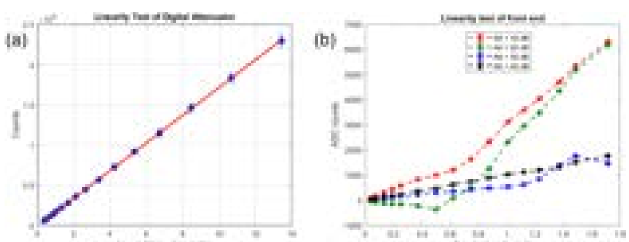

Figure 2: (a) Internal and (b) External attenuation linearity.

INJECTION ANALYSIS

The first specific study case focuses on monitoring the injection process within the accelerator using the hardware injection trigger. The bunch-by-bunch resolution allows to obtain the bucket address the new bunch is injected to, as well as to track its position throughout every turn. This makes it possible to study how injecting beam into different bucket addresses affect the specific bunches.

Empty Machine

Firstly, single bunches are injected into the empty machine at different bucket addresses from 1 to 10. The frequency of the bunch's longitudinal oscillations is obtained from the SUM, depicted in Fig. 3 (a), found to be 34.7 kHz for every injected address, with an average damping time of 151.6 ± 5 µs. On the other hand, the PSD for the X orbit in Fig. 3 (b) shows a combination of two frequencies around 17.5 kHz and 31 kHz, identified as the injection oscillation frequencies. These peaks are much narrower, indicating longer time oscillations.

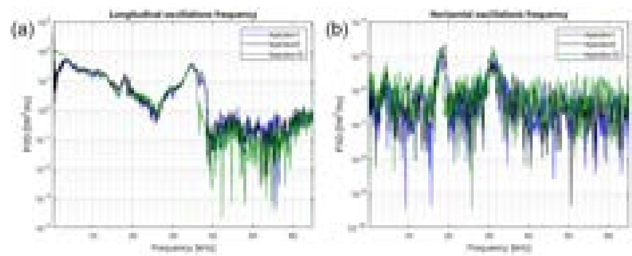

Figure 3: PSD of (a) SUM and (b) X for different injected bunches.

Filled Machine

The next step involves conducting the same injection analysis on a filled accelerator, where bunches are already circulating. In this scenario, additional intensity will be automatically be injected into one of the already circulating bunches when the total intensity is dropped by 1 % (top-up mode), and the effect this injection has on the rest of the bunches will be analyzed.

In every case, the injected bunch is clearly identifiable by the SUM signal, which reaches an absolute maximum and then oscillates over several turns with the previously determined injection frequency. However, this increase in intensity is accompanied by a decrease in another bunch, found to be located 22 bucket addresses (4.2 µs) later for each of the studied injections. This effect, that was first observed in the SUM signal, becomes evident in the orbit analysis, as the bunches with the highest RMS consistently correspond to those located 4.2 µs after the injected one, as Fig. 4 shows. This time aligns approximately with half a turn inside the accelerator. This orbit bump is caused by the effect of eddy currents, which are induced in the vacuum chamber at the end of the injection kicker bump, i.e. approximately half a turn after injection. Given that alterations for both the 40 and 480 bunch filling patterns occur in bunches located half a turn away from the injected one, the observed increase in RMS values for these bunches was attributed to this currents. In order to characterize this excitation, the orbit and PSD of these affected bunches, along with the injected one, are plotted in Fig. 5. The injected bunch (i=10) exhibits a pattern similar to that observed in Fig. 3, with two narrow frequency peaks matching the injection oscillations on an empty machine. Conversely, the distorted bunches (i

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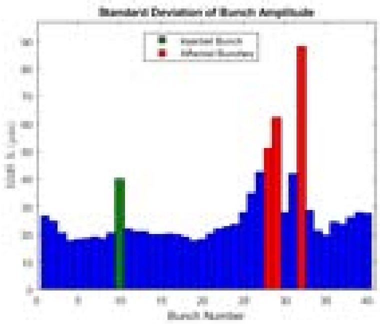

Figure 4: X amplitude when bunch is injected to address 10 in a 40 bunch filling pattern.

= 28, 29, 32) show a much broader frequency peak, centered around 20 kHz. This implies these oscillations are quickly damped in the time domain, unlike those caused directly by the injection.

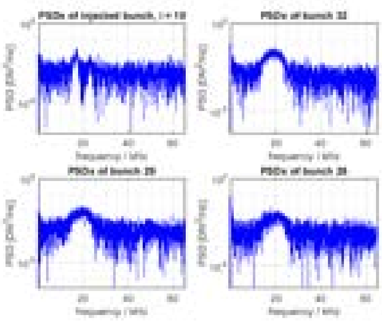

Figure 5: PSDx of orbit for the injected and kicked bunches.

KICKER ANALYSIS

Then, the kicker operation is studied. For this study, the injection trigger is activated without any actual injection, enabling only the desired kickers. For each kicker study, two scenarios are analyzed: MBFB turned on, and off. Since the goal of the feedback system is to damp any oscillations, the beam tunes should be more clearly observed when the system is switched off, though this also results in less beam stability.

Excitation-Vertical

The excitation kicker applies a half-sine wave in the Y plane, with low coupling to the X plane, primarily affecting bunches 31 to 9, although the bunches most impacted by the kick are 39 and 40, as this is where the kick is directly applied. Their maximum Y amplitude reaches 500 µm when the MBFB is enabled, and this value doubles for MBFB disabled. The impact of the MBFB is evident in Fig. 6: with the MBFB on, the bunches oscillate for fewer than 100 turns, whereas without the feedback, the oscillations persist even after 2000 turns. The excitation decay time is found by fitting the orbits to decreasing exponentials, and a linear dependence is found between them and the Y amplitude in Fig. 6. The frequency spectrum plotted in Fig. 7 shows a maximum

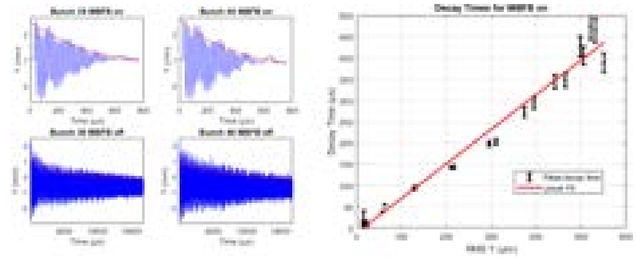

Figure 6: Fit to Y oscillation decay times. Note the different scales.

peak around 41 kHz, which is found to be the vertical tune frequency. Furthermore, additional peaks located at 6, 12 and 18 kHz are evident in for both the horizontal and vertical PSDs, which could match PETRA III's synchrotron frequency of 6.37 kHz [1] and its harmonics.

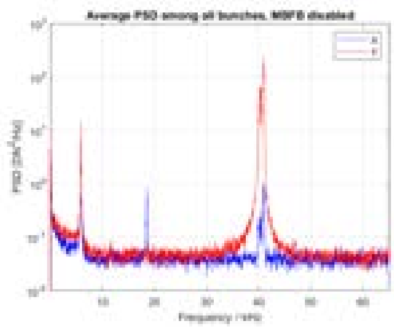

Figure 7: PSD x and y when firing the excitation kicker.

Injection-Horizontal

The PETRA III injection scheme consists of an horizontal off-axis injection with three kicker magnets and a septum magnet [4], which generate and apply half-sine pulses, with a longer pulse length than the vertical kicker. In order to test their effect on individual bunches, the trigger was activated to simulate injection at bunch address 40 without introducing any actual current while firing these three kickers. In this case, the injection frequencies (17.5, 31 kHz) are no longer present, as seen in Fig. 8. However, the round peak around 20 kHz, caused by eddy currents, persists; and an additional sharp peak, at 26.6 kHz appears. No coupling is seen between X and Y planes, showing no vertical excitation from the injection kickers.

Then only one of the injection kickers is used to horizontally excite the beam. In this situation, X orbit amplitudes reach 4 mm when the MBFB is on, and to 6 mm when the MBFB is turned off, while the Y orbit shows more moderate values, around 400 µm, with the MBFB system having minor impact in the vertical oscillations. However, its influence on the X oscillations is significant, seen in Fig. 9, which displays the X orbit of the largest RMS bunches for both feedback and no-feedback scenarios. In the no-feedback case, the oscillations persist for a longer time. Decay times are of the order of 1 ms with MBFB on; and 20 ms with MBFB off. When the obtained results are plotted as a func-

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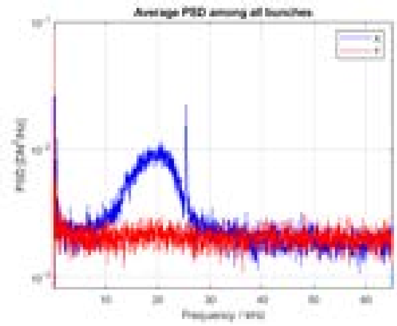

Figure 8: PSD x and y when firing the three injection kickers.

tion of the amplitude for the case of active MBFB a quadratic dependence is found.

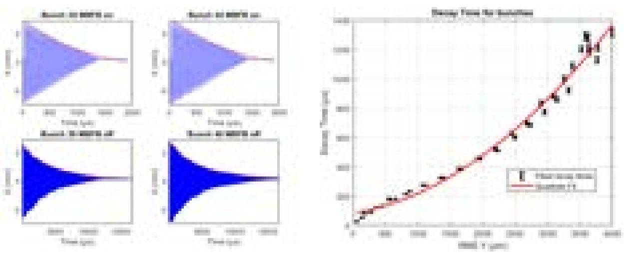

Figure 9: Fit to X oscillation decay times. Note the different scales.

Furthermore, in the frequency spectrum plotted in Fig. 10 a large coupling is appreciated between X and Y planes. The peak frequency for both is 18.6 kHz, identified as the horizontal tune, but also present for the vertical oscillations. Its second and third harmonics, at 37.2 and 55.8 kHz respectively are present, still at both transverse planes. Additionally, new frequency lines emerge at the PSDy when disabling the MBFB at 5.9 kHz, likely corresponding to the synchrotron frequency, and at 41 kHz, previously identified as the vertical tune.

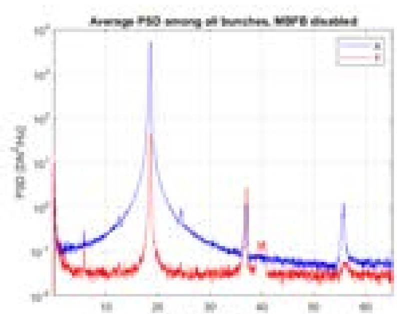

Figure 10: PSD x and y when firing one injection kicker.

INTENSITY TUNE SHIFT

The final case study involves examining how the previously identified tunes vary as a function of bunch intensity. The filling pattern inside the accelerator is changed to 60 circulating bunches, with an inhomogeneous intensity distribution. The excitation kicker was fired with the MBFB enabled, and the bunch-by-bunch Y orbit was analyzed. The highest current (above 0.3 mA/bunch) is found for bunches 51 to 7. PSDy for these bunches is fit to gaussians, in Fig. 11 (a), identifying the peaks as the vertical tunes. Each of the fitted peak values is plotted as a function of bunch intensity in Fig. 11 (b). The relation between the bunch intensity and tune is linear, and the slope for the fitted line is of -2.37 kHz/mA. This result was previously calculated in [5], however, the previously obtained vertical tune shift was found to be of -1.73 kHz/mA.

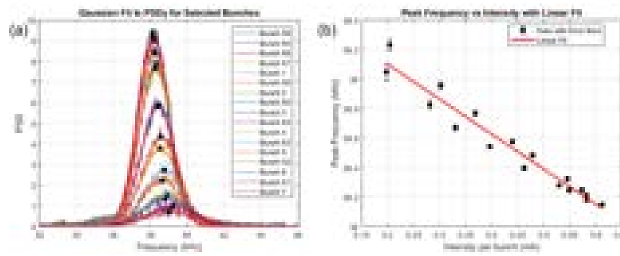

Figure 11: (a) Gaussian fit to PSDy (b) Fit to tune for selected bunches.

CONCLUSION

This paper summarizes the first bunch-by-bunch measurements taken at PETRA III using the Libera Digit500 instrument. The instrument commissioning was successfully carried out and its linearity was tested. While the digital attenuators are linear, some non-linearities were found in the RF front-end.

While injections at an empty accelerator were identified with one longitudinal frequency of 34.7 kHz and two transverse frequencies of 17.5 kHz and 31 kHz, those at a filled accelerator revealed an additional effect caused by eddy currents on bunches 4.2 µs after the initial one, exhibiting a transverse 20 kHz oscillation

Furthermore, the horizontal and vertical tunes were obtained, along with the decay times, and coupling between the horizontal and vertical orbits for the different scenarios. Additionally, an intensity dependent tune shift was observed when applying the excitation kicker with MBFB on.

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