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BUNCH-BY-BUNCH FEEDBACK SYSTEM USED AS A DIAGNOSTIC TOOL FOR MULTI-BUNCH BEAMS IN THE DAΦNE COLLIDER

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Abstract

DAΦNE is an electron-positron collider in operation at INFN-LNF since 2001. Bunch-by-bunch feedback systems installed in each of the two rings allow to store high-intensity and stable beams, by counteracting coupled-bunch instabilities. The feedback systems can be also used as a diagnostic tool able to measure beam parameters, which are significant for the evaluation of the instabilities. In this paper, we first describe the acquisition system used to collect the beam data provided by the feedback systems. Then we report recent transverse tune shift and grow-damp measurements with positron beams, performed using the feedback as a diagnostic tool. These measurements helped to characterize the e-cloud beam instability, which is one of the main factors currently limiting the DAΦNE performances. Finally, we describe the first measurements and feedback system setup designed to automatically record turn-by-turn bunch position displacements when a sudden loss in beam current occurs due to any faults in the collider. This tool can be very useful in identifying the causes of these events and performing beam dynamics studies and code validation.

INTRODUCTION

The DAΦNE lepton collider works at the c.m. energy of 1.02 GeV and includes two independent rings, each 97 m long. The collider has recently operated to characterize the never observed before kaonic deuterium transition [1]. DAΦNE has delivered to the SIDDHARTA-2 detector a data sample of the order of 1.5 fb^{-1}, an integrated luminosity well beyond the experiment request. In addition, most of the provided data have very high quality [1]. These remarkable results have been obtained by performing continued machine tuning, as well as dedicated machine studies.

The large luminosity provided to the experiments was the result, among other things, of the high beam currents accumulated in the rings. In 2024, the maximum stable beam currents stored in collision have been of the order of 1 A and 1.65 A, respectively for the positron and electron beams. Instabilities due to e-cloud strongly affect the positron beam dynamics, and they are one of the main factors limiting the maximum stored positron current.

To better characterize the strength of the e-cloud effects, an extensive campaign of e-cloud simulations and measurements has been performed in 2024, with the first results presented in Ref. [2]. Tune-shift and grow-damp measurements rely on the bunch-position signals, which were digitized by the signal processing unit of the bunch-by-bunch transverse feedback systems installed in the positron ring [3, 4]. These real-time systems, designed to counteract coupled-bunch instabilities, and to store high-intensities and stable beams, were therefore used as a diagnostic tool to measure beam parameters able to characterize the instabilities themselves.

The bunch-position signals acquired with the feedback system allow to study in detail the phenomenology of beam dynamics in case of fast beam losses. This approach can also provide indications about the causes of these events. The main difficulty here is to rightly trigger the acquisition, since the available buffer of recorded data is limited.

In the next section, the diagnostics acquisition system used for the measurements will be briefly described. Then, results of beam measurements using this diagnostic tool will be described, starting with tune-shift and grow-damp data, and ending with beam-death analysis.

ACQUISITION SYSTEM DESCRIPTION

The horizontal and vertical feedbacks act on the positions of the bunches centroids. The feedback corrections are provided by stripline kickers and they modify the transverse momenta of the particles. For each bunch and at a given turn, the signals from the horizontal or vertical electrodes of one BPM are subtracted from each other and sent to the signal processor (Fig. 1). These analog signals, proportional to the positions of the bunches centroids, are digitized in the ADC (12 bits, f_{sample} = 368.7 MHz, BW = 1.3 GHz) and then elaborated in FPGA to compute the correction signals, which are converted to analog in the DAC (Fig. 1). After going through RF amplifiers (Amplifier Research 250A250AM3), the corrections are sent to the horizontal or vertical kickers.

The acquisition memory in Fig. 1 has a circular buffer, i.e. data are recorded continuously, with old values being replaced by new ones. Data are recorded for each bunch turn after turn or with a user-defined down-sampling factor. Recording every turn, it is possible to obtain 34 ms of horizontal or vertical-position data for each bunch, by providing a trigger to the DIMTEL which freezes the memory buffer.

The trigger can be internal and sent by using the system interface, as was done during the tune-shift and grow-damp measurements. Otherwise, the trigger can be provided by an external system when a certain condition occurs. This second method was used during beam-death measurements, when the trigger fired as soon as the derivative of the average beam current provided by a DC current transformer went

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below a certain threshold. Due to the circular buffer, it was possible for those measurements to record data occurring before the trigger fired. This was essential, since the beam was lost by the time the trigger fired.

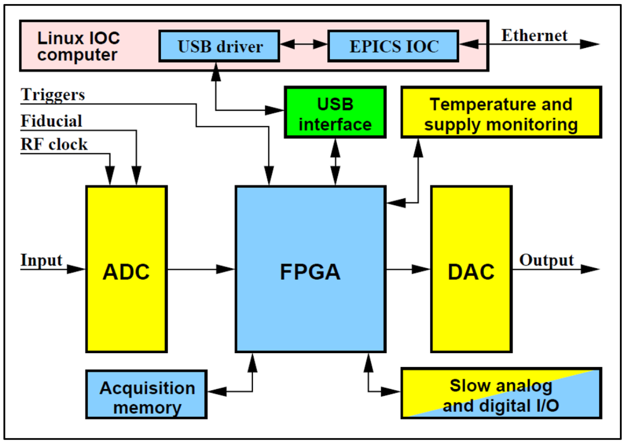

Figure 1: Block diagram of the signal processing unit of the bunch-by-bunch transverse feedback (DIMTEL iGp12-120F [5]).

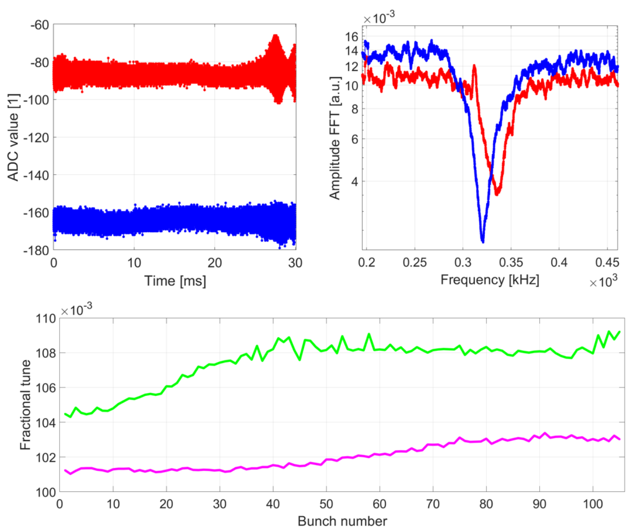

Figure 2: Top left: horizontal position of bunch 1 (blue) and 105 (red) versus time. Beam of 105 contiguous bunches with a total intensity of 790 mA. Top right: DFTs of the corresponding signals in the top-left plot. The focus is on the notches created by the bunch-by-bunch feedback. Bottom: tune shift along the batch for a beam intensity of 790 mA (green) and 350 mA (magenta).

The data collected in the memory can be retrieved by EPICS (Fig. 1) and uploaded to an external PC by using the Ethernet protocol and appropriate libraries for Matlab [6].

TUNE SHIFT MEASUREMENTS

The strength of the e-cloud affecting the positron beam in a non-colliding configuration was evaluated, at different currents up to 800 mA, by performing horizontal tune-shift measurements along the batch [1,2]. Each bunch-position signal was recorded every machine turn for 30 ms, keeping the horizontal feedback on (Fig. 2, top left). The tune of a given bunch was obtained by performing a discrete Fourier transform (DFT) of the position signal, and by considering the frequency where the notch created by the feedback had its minimum (Fig. 2, top right). Since the revolution frequency is 3.1 MHz, a resolution of 10^{-5} in the fractional tune is obtained for 30 ms long signals. A moving average filter was applied to the Fourier-transformed signal to better identify the minimum of the notches. Convergence studies were performed to determine the appropriate length of the filter sliding window (100 points). Figure 2 (bottom) shows examples of tune-shift measurements for two different beam intensities. The tune can also be measured by turning off the horizontal feedback, and in this case a peak appears in correspondence of the betatron frequency. Nevertheless, without recurring to sophisticated tune measurements techniques (as in Ref. [7]), we observed that, in the latter configurations, peaks were too broad, which in turn affects the measurements precision. In addition, for a beam pattern of 105 contiguous positron bunches (used in collisions), measurements with the feedback off can be performed only up to 600 mA.

Horizontal tune-shift measurements for 105 contiguous positron bunches were performed three times in 2024 (Fig. 3). The relatively large differences above 600 mA between the old (green) and new (blue or red) data can be due to scrubbing, and to the significant machine optimizations and fine tuning applied along the year. For the more recent measurements, the tune shifts start to decrease above 600 mA, going from $6 \cdot 10^{-3}$ to $5 \cdot 10^{-3}$. This was unexpected, although smaller tune shifts at higher intensities have been already measured at other accelerators [7].

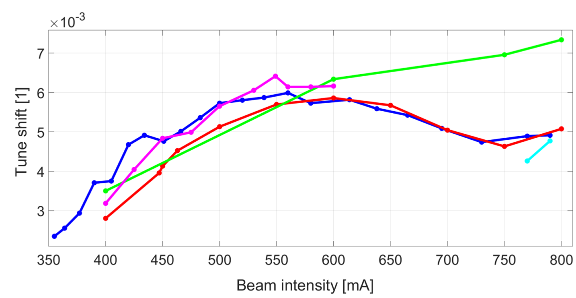

Figure 3: Tune shift measurements versus positron beam intensity for 105 contiguous bunches. Each shift is the difference between the maximum and minimum tunes along the batch. The green, red and blue curves refer to horizontal tune shifts recorded respectively in February, June and July 2024. The magenta line represents horizontal tunes measured in June without using the solenoids. Vertical tune shifts measurements taken in July are indicated with the cyan curve.

Data were also recorded after having turned off the solenoids in the straight sections, which are needed to reduce the e-cloud effects. Comparing data taken in the same measurement session with or without solenoids (red and magenta curves), one can see that the tune shifts are larger without

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solenoids, as expected. Moreover, it was impossible to inject more than 600 mA of beam current without solenoids.

First vertical tune-shift measurements were also taken, providing values at around 800 mA only slightly below the horizontal ones (Fig. 3). Finally, configurations with electron beams were considered. Tune shifts were below 10^{-3}, even for 110 contiguous bunches with a beam current of 1.5 mA.

GROW DAMP MEASUREMENTS

To characterize the horizontal multi-bunch instability of the positron beam due to the e-cloud, grow-damp measurements were performed [1, 2, 8]. The beam instability was induced by switching off the horizontal feedback for a given time interval. The recorded bunch-position signals were used as input for the modal analysis, which provided the growth rates of the different coupled-bunch modes.

Figure 4 (top left) show the horizontal-position signals of bunches 1 and 61, obtained from grow-damp measurements where the horizontal feedback was switched off during the first 0.15 ms. The DAΦNE harmonic number is 120, which corresponds to the number of possible coupled-bunch modes (from 0 to 119). The modal analysis of the 105 bunches revealed 119 as the dominant mode (Fig. 4, bottom right), which is typical for e-cloud localized in wigglers and bending magnets. The bunch-by-bunch phase shift corresponding to mode 119 is 3°, therefore we would expect that bunches 1, 31, 61 and 91 are shifted in phase by 90° one after the other. This is qualitatively confirmed by Fig. 4 (top right).

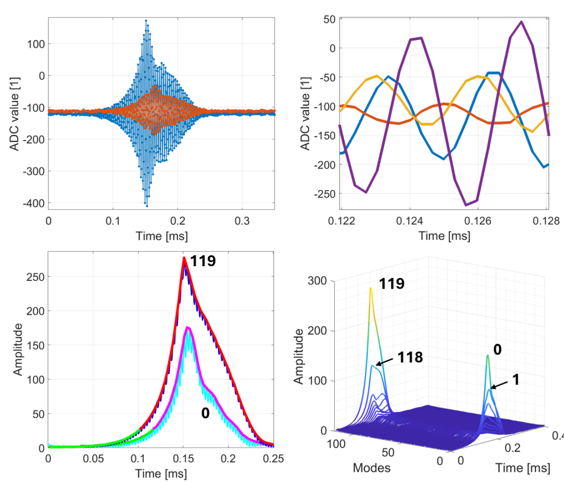

Figure 4: Top left: horizontal position of bunch 1 (orange) and 61 (blue) versus time. Beam of 105 contiguous bunches with a current of 800 mA. Top right: zoom of the first plot, where the horizontal-position signals of bunches 31 (yellow) and 91 (purple) are added. Bottom left: amplitude of mode 0 (cyan) and 119 (blue) versus time. The corresponding envelopes are in magenta and red. The portions in green are considered for the exponential fits. Bottom right: envelopes of the 120 possible modes versus time.

Exponential fits of the envelopes at small amplitudes (see e.g. the green curves in Fig. 4, bottom left) provided the grow rates of the modes. Figure 5 shows the results related to two sets of grow-damp measurements taken in 2024. As expected, grow rates in general increase with higher beam currents, reaching values of almost 50 ms^{-1} at 800 mA for both modes. For a given measurement, the grow rates of modes 0 and 119 are relatively close to each other.

Grow-rate estimations can be inaccurate, because they can vary by a few percent depending on the envelope portions used for the fits. The evaluated grow rates of modes 0 and 119 at 800 mA are respectively 49 ms^{-1} and 47 ms^{-1}, and this is in contrast with the fact that mode 119 grows faster than mode 0 (Fig. 4, bottom left). A simpler approach to quantify the strength of the different modes would be for instance to evaluate their amplitudes at a fixed time.

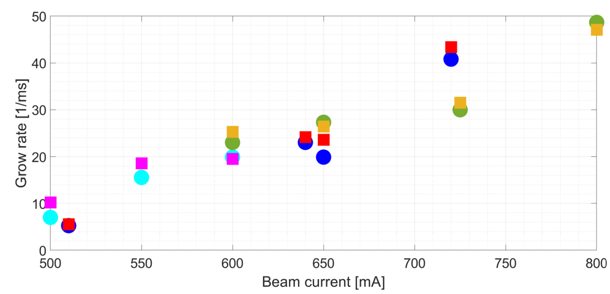

Figure 5: Grow rates of modes 0 (circle) and 119 (square) versus beam current, obtained from modal analysis of grow-damp measurements with 105 contiguous positron bunches in non-collision configuration. Measurements were taken in April (blue, red) and July (green, yellow) 2024. A third set of data (cyan, magenta) was taken in July, after having switched off the solenoids installed in the ring.

A third set of grow-damp measurements was taken after switching off the solenoids (Fig. 5). At 600 mA, we found that modes 0 and 119 grow slower without solenoids, even though vacuum pressure in different points of the ring increased by several order of magnitudes due to enhanced e-cloud density. This counter-intuitive result is likely due to the larger vertical emittance of the beam without solenoids, which makes the beam slightly more stable when the feedback is turned off.

BEAM DEATH MEASUREMENTS

Relatively fast (≈ 0.1 ms) current drops for positron beams of 900 mA were induced in three different ways. First, the horizontal feedback was switched off, simulating a fault of the power supplies or amplifiers in presence of the circulating beam. Since faults related to timing and magnets power-supplies can occur during operation, as a second test we forced the beam loss by making the injection kickers misfire during machine filling. Finally, the RF mode-zero feedback used to counteract the beam loading was switched off.

Figure 6 (top left) shows the horizontal positions of the first and last bunches, obtained from the beam measurements in presence of kicker fault. The baselines of the oscillations approach zero at the fault time, suggesting that part of the

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beam is lost. A second large modulation in oscillations occurs in correspondence of the RF interlock, which triggers as a consequence of the beam losses happened 3 ms before.

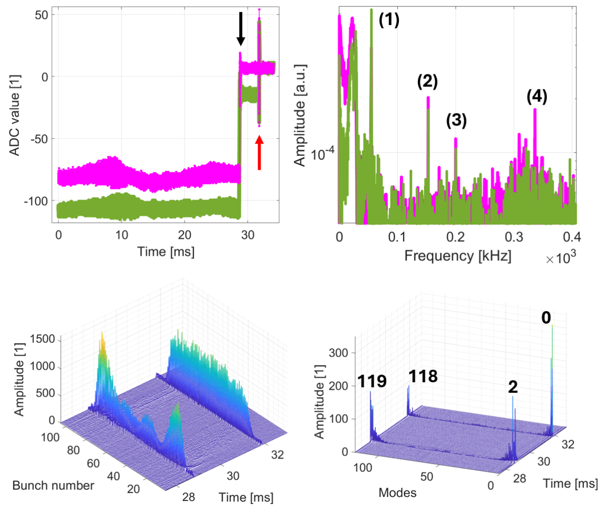

Figure 6: Beam of 105 contiguous bunches with a total current of 860 mA and in non-collision mode. Top left: horizontal position of bunch 1 (green) and 105 (magenta) versus time. The fault of the injection kickers occurs at 28.7 ms (black arrow), while the RF interlock happens at 31.8 ms (red arrow). Top right: DFTs of the corresponding signals in the top-left plot, by considering only the signals portions between the fault and RF interlock times. The frequencies of the marked peaks are in the order 55 kHz, 153 kHz, 200 kHz and 336 kHz. Bottom: envelopes of the bunches horizontal-positions (left) and modes oscillations (right) as a function of time. The dominant modes are marked.

Analyzing in frequency domain the signals portions between the fault and interlock times (Fig. 6, top right), four peaks emerge, in addition to the one at the synchrotron frequency (28 kHz). The peaks at 55 kHz, 153 kHz and 200 kHz were also observed by Fourier-transforming the signal portions before 28.7 ms, thus they are not related to the fault. On the contrary, the typical feedback notch at around 330 kHz (horizontal betatron frequency) seen before 28.7 ms was replaced by a peak after the fault (Fig. 6, top right). The amplitudes of bunch oscillations are in general significant only in correspondence of the fault and interlock times (Fig. 6, bottom left). The dominant modes are number 2 and 119 at 28.7 ms, 0 and 118 at 31.8 ms (Fig. 6, bottom right).

Examining in detail the other two scenarios of beam loss, it was possible to have a first guess on the cause of a fast and unexpected drop in beam current occurred during operation. Careful comparisons suggested that the fault could be directly related to the horizontal feedback, or to fast horizontal instabilities of unknown origin which the feedback is not able to damp. For example, Fig. 7 (top left) shows peaks at the horizontal and vertical betatron frequencies, as well as at the second harmonic of the horizontal frequency. These three peaks appear in the configuration with the horizontal feedback switched off (Fig. 7, bottom left). The frequencies are slightly slower, but this can be due to a different machine configuration, as well as to the different beam intensity. The three peaks are absent in the other two configurations (Fig. 7, right), suggesting that the kickers and the RF feedback are not responsible for the beam loss occurred during operation.

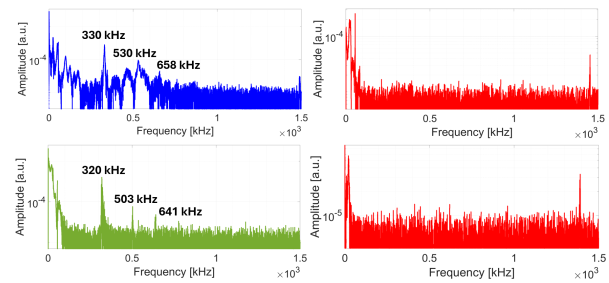

Figure 7: DFT of the vertical-position signal of the first bunch, related to the measurement with beam loss due to an unknown reason (top left), injection-kickers misfire (top right), switch off of the horizontal feedback (bottom left) and of the RF mode-zero feedback (bottom right). Only the signal portion between the fault and RF interlock times are considered for each DFT. The bunches are 105, except for the case of horizontal feedback off (110 bunches). The beam currents are 600 mA (RF feedback off), 860 mA (kickers misfire), 870 mA (unknown cause) and 900 mA (horizontal feedback off). The frequencies of selected peaks are shown.

CONCLUSIONS

The bunch-by-bunch feedback systems at DAΦNE can be used as an important diagnostics tool. The e-cloud beam instability for positron beams was better characterized thanks to transverse tune-shift and grow-damp measurements. For the more recent data we found that the horizontal tune-shift tends to decrease above 600 mA, motivating further studies to better understand this behaviour. Values slightly increase when solenoids are switched off, as expected. Vertical tune shifts at 800 mA are close to the horizontal ones, while measurements with electron beams revealed very small values.

Grow-damp measurements turning off the horizontal feedback revealed grow rates at 800 mA of almost 50 ms^{-1} for the modes 0 and 119. Switching off the solenoids led to higher grow rates, due probably to larger vertical beam sizes.

The feedback was also used as a diagnostics tool to characterize three faults leading to fast beam losses. The analysis suggested the reason of an unexpected drop in current occurred during operation. More measurements will be needed to study other types of malfunction, so to make the characterization of unknown faults more precise.

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