

SLOVAK UNIVERSITY OF TECHNOLOGY IN BRATISLAVA
Faculty of Electrical Engineering and Information Technology
Institute of Electronics and Photonics

Signal Processing Techniques For Transverse Feedback Systems In Hadron Accelerators

Dissertation abstract
to obtain academic degree Philosophiae Doctor (PhD.)

Field of study: Electrical engineering
Subject of specialization: Electronics and Photonics
Form: External

Registration number: FEI-104402-117003

Author: Dipl.Ing. Gerd Kotzian
Supervisor: doc. Ing. Daniel Valúch, PhD.
Consultant: prof. Ing. Viera Stopjaková, PhD.

Bratislava/Geneva, October 2025

Dissertation thesis was elaborated at Radio-Frequency Group, Accelerators Systems Department, CERN, Geneva, Switzerland.

Author: **Dipl.Ing. Gerd Kotzian**

email: gerd.kotzian@pm.me

Supervisor: **doc. Ing. Daniel Valúch. PhD.**

Accelerators Systems Department

CERN

1, Esplanade des Particules

Geneva, Switzerland

email: daniel.valuch@stuba.sk

Consultant: **prof. Ing. Viera Stopjaková, PhD.**

Institute of Electronics and Photonics

Faculty of Electrical Engineering and Information Technology

Slovak University of Technology in Bratislava

Ilkovičova 3, 841 04 Bratislava

email: viera.stopjakova@stuba.sk

Opponents: **Prof. Themistoklis Mastoridis**

Physics Department

California Polytechnic State University

1 Grand Avenue, San Luis Obispo

CA 93407, USA

email: tmastori@calpoly.edu

Dr. Nicolas Mounet

Beams Department

CERN

1, Esplanade des Particules

Geneva, Switzerland

email: nicolas.mounet@cern.ch

Dissertation abstract was distributed on:

PhD. defense taking place on 19.11.2025, 11:00 in front of a committee for field of study Electrical Engineering, subject of specialization: Electronics and Photonics.

Chair of the examination committee

prof. Ing. Alexander Šatka, CSc.

Dean FEI STU in Bratislava

prof. Ing. Vladimír Kutiš, PhD.

Anotácia

Techniky spracovania signálov pre systémy priečnej stabilizácie zväzku v hadrónových urýchľovačoch

Systémy priečnej stabilizácie zväzku sú vitálne pre hadrónové urýchľovače pracujúce s vysokou intenzitou zväzku.

Dôležitá súčasť takéhoto systému je výkonná jednotka digitálneho spracovania signálu. Súčasné číslicové technológie umožňujú implementáciu veľmi pokročilých algoritmov a analytických techník pre extrakciu dôležitých parametrov urýchľovača, alebo samotného spätnoväzobného systému.

Výskum sa bude zaoberať možnosťami extrakcie parametrov spätnoväzobného systému na základe matematických formalizmov teórie signálov a sústav s použitím aktívneho vybudenia obiehajúceho zväzku týmto systémom a len s použitím informácie získanej z tohoto systému. Minimálne skúmané parametre pre optimálnu prevádzku systému sú fáza a oneskorenie v uzavretej spätnoväzobnej slučke (vrátane zväzku). Súčasné techniky postavené na meraniach externými prístrojmi sú časovo veľmi náročné, poškodzujú obiehajúci zväzok a nedosahujú požadovanú presnosť.

Druhým cieľom výskumu je navrhnuť a implementovať metódy extrakcie kritických parametrov urýchľovača (parameter "tune" a časová konštanta útlmu oscilácií pre každý jednotlivý bunch) s použitím nedeštruktívnych manipulácií so zväzkom bez vytvárania strát častíc a degradácie kvality zväzku. Znalosť týchto parametrov je dôležitá pre dosiahnutie stability obiehajúceho zväzku a spoľahlivej prevádzky urýchľovača, ale v súčasnosti tieto parametre nie sú jednoducho, alebo vôbec dostupné.

Abstract

Signal processing techniques for transverse feedback systems in hadron accelerators

Transverse feedback systems are essential for stable operation of all hadron accelerators with high intensity beams.

An important component of such a system is a powerful digital signal processing unit. Current digital technology allows implementation of very advanced algorithms and analysis techniques to extract key parameters of the accelerator and the feedback itself.

The traditional techniques based on external instruments are time consuming, destructive to the beam and do not provide required precision. The research will aim at possibilities of feedback parameter extraction and performance optimization using only active manipulations of the beam by the transverse feedback system itself and analysis of data acquired from it. Based on formalisms of signals and systems theory, the minimum required parameters will be the closed loop phase and delay. These are essential for optimum feedback operation.

The second aim of the research will be to study and implement methods to extract vital accelerator parameters (e.g. the bunch by bunch machine tune and the damping time) using active manipulations of the beam by the transverse feedback system itself without degradation of the beam parameters. Accurate knowledge of these parameters is essential for ensuring beam stability and the reliable operation of the accelerator.

Easy access to these parameters is important for automated TFB setting up, performance monitoring, or efficient troubleshooting. This kind of information was not accessible until now.

Contents

Introduction	1
1 Current state of the problem	3
1.1 TFB principle of operation	3
1.2 TFB technology, key parameters, and their determination	5
1.3 Analogue and digital signal processing for TFBs	10
1.4 Extraction of valuable machine parameters from TFB data	11
1.5 TFB status monitoring	12
2 Research objectives	13
3 Methods	15
3.1 System modeling	16
3.1.1 Beam representation in z-domain	17
3.1.2 Sensor model	23
3.1.3 TFB controller	30
3.2 TFB Parameter Identification	35
3.3 Transverse phase space reconstruction	36
3.3.1 Spatial method	37
3.3.2 Temporal method	39
3.4 TFB parameter extraction	41
3.4.1 TFB gain	43
3.4.2 TFB phase	43
3.4.3 TFB delay	44
3.5 Accelerator parameter extraction	45

3.5.1	Bunch-by-bunch tune	45
3.5.2	Damping time	45
4	Results	47
4.1	Measurements	47
4.1.1	Method verification	48
4.1.2	TFB parameter measurement results	65
4.1.3	Accelerator parameter measurement results	70
4.2	Extraction of vital accelerator parameters in real time	73
4.3	Digital filter design to reduce tune dependence	74
	Conclusions	87
	Zhrnutie dosiahnutých výsledkov	89
	Záver	95
	Author's publications journals	97
	Author's publications proceedings	99
	References	105

Introduction

The *European Organization for Nuclear Research* (CERN) was founded in 1954. It is a particle physics laboratory situated at the border between Switzerland and France, where it operates a chain of particle accelerators in order to investigate the constituents of matter. The largest of these accelerators is the *Large Hadron Collider* (LHC) [1] depicted in Figure 1. With its circumference of 27 km it is the most powerful particle accelerator ever built [1] (at the time of writing). In the LHC two beams made up of protons or ions are accelerated to energies reaching 6.8 TeV and collide at four interaction points. Highly sophisticated particle detectors installed at these interaction points detect the fragments of the collisions and analyse their trajectories. The outcomes of these experiments are expected to give new insights in many fields of modern high energy physics and lead to a better understanding of the laws of nature.

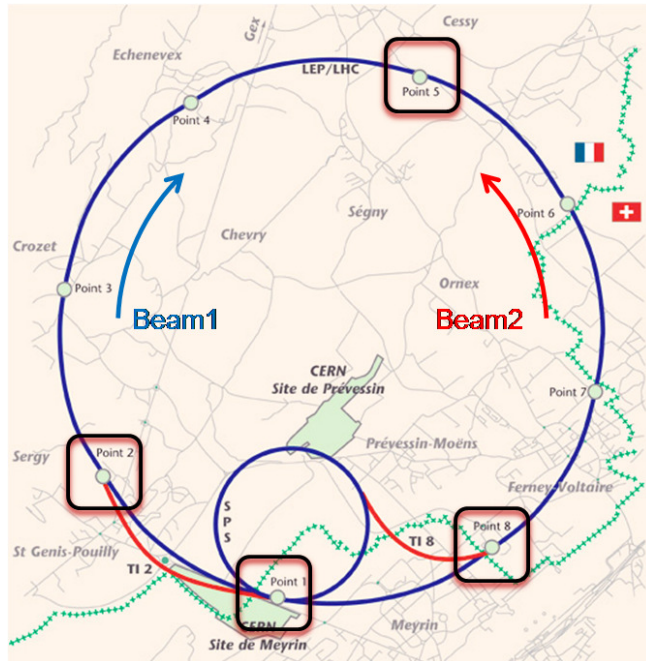


Figure 1: CERN and the LHC.

Transverse Feedback systems (TFB) are an essential part of each high energy circular particle accelerator, regardless if proton [2–4], heavy ion [5, 6], electron-positron storage ring [7, 8] or

a synchrotron light source [9, 10] to name only few.

Their task is to stabilize high intensity beams by suppressing any transverse instabilities driven by machine impedance [11, 12], reduce transverse motion induced by external perturbations [13, 14], or preserve emittance of the injected beam by rapid damping of injection oscillation transients [15, 16].

Working on these systems requires broad interdisciplinary skills and knowledge, for example, beam dynamics, analogue electronics, digital electronics, *Radio Frequency* (RF) engineering, high voltage systems, vacuum systems, high intensity beam interaction with the machine to name only few.

With the arrival of very powerful programmable digital electronics more than two decades ago, the data and signal processing hardware is no longer the limiting factor to the complexity of implemented algorithms and digital signal treatment. This opened completely new possibilities for transverse feedback systems in accelerators. The damping or stabilizing function of the transverse feedback is no longer the only service these systems are expected to provide. The TFBs are used now for example, for beam cleaning [17–19], real time transverse activity monitoring and instability detection [20] as well as beam transfer function measurement [21]. Transverse feedback can be a source of controlled machine impedance, allowing for special measurements such as direct Landau damping strength measurement [22], impedance measurement of individual accelerator components (e.g. low-impedance collimators) by means of high precision tune shift detection techniques [23] or impedance measurements of insertion devices in light sources by the grow-damp method [24]. With full-resolution beam position data now available in digital form [25], the focus has shifted beyond the core feedback functionality (which remains necessary) toward added-value services aimed at enhancing accelerator performance and operation.

Engineers working on transverse feedback systems need to thoroughly understand digital signal processing techniques to be able to identify their potential for TFBs, and the data provided by them. With modern digital technology, it is possible to extract the key parameters of the accelerator and the TFB itself from the TFB internal data streams. Such work involves also system design and digital signal processing which are subject of this thesis.

Chapter 1

Current state of the problem

1.1 TFB principle of operation

In Figure 1.1 the key components of a transverse feedback system are outlined. At the injection point where the beam is received from a previous accelerator using a transfer line, there are transverse oscillations launched around the target orbit due to imperfections in this process.

The beam position is measured every turn by one or more position monitors composed of a coupling device to the beam (pick-up) and signal conditioning electronics [26, 27]. This combination is often referred to as a beam position monitor or a beam position measurement module (BPM).

A correction signal is then calculated based on the position data and transformed to the point in the accelerator where the transverse kicker is located such that the overall phase in the feedback loop is negative and the loop is stabilizing the beam. In the early days, the calculation of feedback signals was fully analog, using filters and delay lines, often hundreds of meters [2, 28], or even a few kilometers long [29]. The time alignment of the processing chain delay T_{signal} to the beam time-of-flight T_{beam} between the position monitors and the transverse kicker is a crucial factor for the transverse feedback to work correctly. Fixed cable delays are not compatible with accelerating beams, so complicated tricks needed to be implemented to cope with a decreasing time-of-flight delay T_{beam} during the energy ramp [30].

If multiple beam position monitors can be installed in the machine with an ideal 90° betatron phase advance between them, the required feedback phase can be obtained by (analog) vector combination of the two (or more) position signals creating a “virtual pick-up”[31].

The correction signals are finally amplified and fed to kickers which deflect the beam and close the feedback. When a lower deflection voltage and high bandwidth is needed, typically

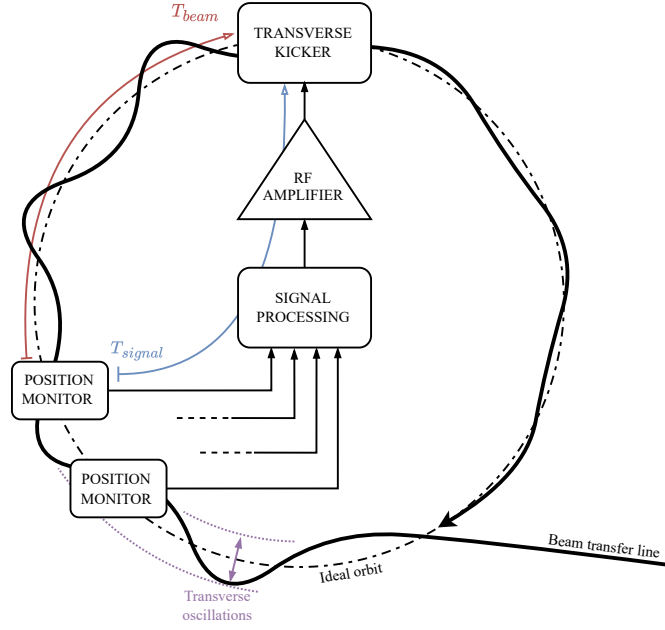


Figure 1.1: Principle blocks of a transverse feedback system in a circular particle accelerator.

terminated strip-line kickers and solid state amplifiers are used (e.g. [32]). If a high deflection is needed e.g. for highly relativistic beams, high power tetrode based amplifiers feeding unterminated E-field kickers are often used (e.g. [33]).

The availability of the first fast analog to digital converters and digital memories immediately allowed for the replacement of the bulky fixed cable delay lines and introduced the possibility for the TFB to follow the accelerating cycle. For example, at CERN's Super Proton Synchrotron, these efforts date back to the beginning of the 1980s [34–36]. With advancements in digital technology in the 1990s the next natural step was to introduce full digital signal processing with digital filtering [37].

In hadron machines, bunch length is comparable with the length of the RF bucket. In smaller synchrotrons, this is typically hundreds of nanoseconds. Digital low-level RF systems therefore can sample the passing bunch at many points and can easily detect an intra-bunch motion. If such a TFB is equipped with pickups and deflectors with sufficient bandwidth, an intra-bunch feedback can be realized to stabilize the head-tail motion. Bunch length in the largest synchrotrons is typically nanoseconds, but modern multi giga-sample per second digital systems and GHz bandwidth amplifiers and kickers allow us to also realize intra-bunch feedbacks capable of stabilizing head-tail motion of such short bunches [38].

Today's digital technology offers virtually unlimited resources for advanced signal processing and data storage.

1.2 TFB technology, key parameters, and their determination

Key TFB parameters are the closed loop gain, feedback phase and loop delay. Their adjustment and monitoring is essential for correct feedback operation. However, for machines like the LHC, only the correct operation of the TFB is not enough, we must achieve optimal (and beyond) operation [39, 40].

Transverse feedback systems were introduced in the early days as a remedy against resistive-wall transverse beam instabilities (due to the increasing beam intensity). Back at the time, the engineers had identified which were the key parameters of the TFB and they designed procedures to adjust them [7, 9, 29, 41–44]. Nevertheless, they did not have the means to directly measure, or determine these parameters. The TFB setting-up involved a lot of indirect methods, observation of beam losses while scanning parameters, finding the loop stability limit by monitoring the transmission, and some "educated guesswork" or gut feelings.

Loop delay settings, for example, are an important factor contributing to the phase margin of transverse feedback systems [7]. In particular, the loop delay is directly related to the usable bandwidth of a TFB, that is, the maximum frequency f_{max} . The phase shift $\Delta\varphi$ introduced by delay mismatch ΔT at a given frequency, is described by the formula

$$\Delta\varphi = 360^\circ \Delta T f. \quad (1.1)$$

Considering a feedback system which is designated for and operated up to 100 MHz, as for the CERN *Proton Synchrotron Booster* (PSB) [45], one obtains from (1.1) a maximum allowed delay error of 0.25 ns to not exceed an acceptable phase error of 10°. This means that all delays contributing to the control loop, such as cable connections, RF amplifier components, or signal and filter processing delays, must be known and adjusted with a high degree of accuracy, otherwise the anticipated TFB performance might not be reachable.

As an added complication, continuous adjustments of a TFB's loop delay are required within the acceleration cycle, to compensate for the propagation delay changes as particles are getting faster. This problem was addressed as early as in the 1960s. First TFB control loops were built which used switchable coaxial delays for automatic delay compensation [46–49] as the beam was accelerated. The implementation in 1977 was based on hard-wired *Emitter Coupled Logic* (ECL) gates, and allowed variable delays of 2.7 ns discrete step size, and a 9-bit digital control word [47]. The same technology was exploited for the PSB [44], and further improved for a step resolution of 1 ns. This implied that the tolerance of the delay adjustment had to be further improved to better than a fraction of a nanosecond in order to reach the target bandwidth.

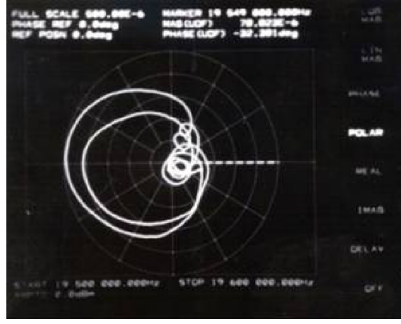
At the time, having had no other means to evaluate the overall loop delay, each individual component of the TFB signal chain needed to be measured. Its group delay and other electrical parameters were entered into a table. The total loop delay was worked out manually. Each row contains data about one system element, evaluated for both planes. These listed values had to be determined to within a fraction of a nanosecond since the table was used to calculate the final values for the fixed and variable delays to be programmed into the hardware. This method relied on systematic and accurate measurements of each and every contributing delay and other system parameters, making it quite labour intensive and prone to all sorts of errors. This is what we call the "Spread-sheet method", which was used for many years.

Later methods of measuring the loop phase and delay involved external instruments such a *Vector Network Analyser* (VNA). A VNA is an active device that measures complex transfer functions of a system. The instrument injects a sinusoidal excitation and measures the frequency response in a complex format. The VNA can be used as a standard RF instrument to measure transfer functions of individual RF devices (TFB building blocks, like amplifiers, cables, or filters), or an overall transfer function of the entire TFB system including the beam. As an example, Figure 1.2 shows two measurements of a circulating beam in the CERN *Super Proton Synchrotron* (SPS) accelerator using a classical VNA to estimate the feedback parameter settings of an active transverse feedback. The measurements presented were made in the early ~2000's, and the method has not evolved much since then.

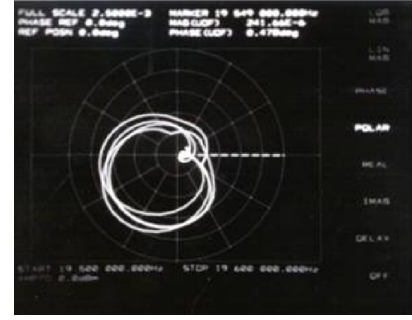
Measuring the system transfer function through the beam provides a basis for evaluating TFB parameters and performance, but many problems remain. The beam circulating in the machine must already be stable without the feedback, which is not always the case. In cycling machines, the beam circulates for only a few seconds (as little as 500 ms in the injector chain, up to 14 s in the larger synchrotrons). In the PSB, the time required for a meaningful measurement is at least 100 ms. As the PSB cycle does not include a period when the machine is not accelerating (so-called flat top), it required preparation of a special magnetic cycle dedicated for TFB VNA measurements [50]. The creation of a dedicated machine cycle means additional work for the operators to configure, adjust, and verify the accelerator and all necessary components – time-consuming and cost-intensive tasks.

Another problem arises from the noise floor of the VNA instrument and its dynamic range. To obtain only remotely usable readings, many circulating bunches must be excited in order to obtain a sufficiently high return signal for the VNA. However, transverse feedbacks are essential for stable accelerator operation and TFBs are one of the first systems to be set-up. Large machines like the LHC are typically not able to handle more than a few circulating bunches at this stage. In case of the LHC, this is typically 5 to 8 individual bunches (out of 3564 possible) of very low intensity

¹Taken from [1], section 14.3.2 on page 100. The images are reproduced in their original quality as provided in the publication.



(a) Horizontal plane @20 MHz



(b) Vertical plane @20 MHz

Figure 1.2: Use of a VNA to measure the beam transfer function with active TFB¹.

($< 1/10$ of maximum). A train of nominal intensity bunches is unstable without a fully functional TFB. The use of a VNA to measure the TFB parameters is therefore extremely delicate at this point in time.

The use of the VNA technique in the LHC suffers from another problem - the LHC is the largest particle accelerator ever built. With a circumference of 27 km, one turn takes $88.9 \mu\text{s}$ at almost the speed of light. The circulating bunches must be evenly spaced around the machine circumference to provide the VNA with regular repetitive response signals, otherwise it cannot measure anything useful within the frequency point measurement window. Increasing the measurement time does not help, since prolonged exposure of the beam to the VNA excitation causes it to oscillate in the lattice, rapidly increasing its transverse emittance, and quickly losing the beam at the collimators.

VNA measurements are typically destructive to the beam, very time consuming, and do not provide the required accuracy. The interpretation of the results is not easy because the VNA measures not only the TFB but the entire accelerator. For example, the VNA method was used to set-up and validate the TFB in the PSB accelerator (see Figure 1.3, showing incorrect loop delay setting and incorrect feedback phase configuration). If the system was already in a reasonable state (e.g. the beam position monitor gain was adjusted, and the coarse cable delays were reasonably trimmed), setting it up for one beam type easily took a whole day. The VNA method, with many minor improvements is used at the LHC, but it still takes a full 8 hour shift to set up and validate the TFB performance here. With operating costs of 42'000 € per hour² and extremely scarce machine time, this is definitely not ideal.

In the CERN PS Booster, after the VNA measurements with dedicated cycles, also the phase scan measurements were performed, to validate the TFB system performance [50]. The TFB was set in closed loop mode and for a given accelerator tune the feedback phase was scanned over the entire range from 0 to 360 degrees. The beam transmission was measured over the plateau. Phase scans allowed identification of an optimal loop gain as well as evaluation of the feedback

²Assuming 1.1 billion CHF allocated resources for 2009-2012, 9 months of LHC operation per year, and an exchange rate of 1 CHF=1 €.

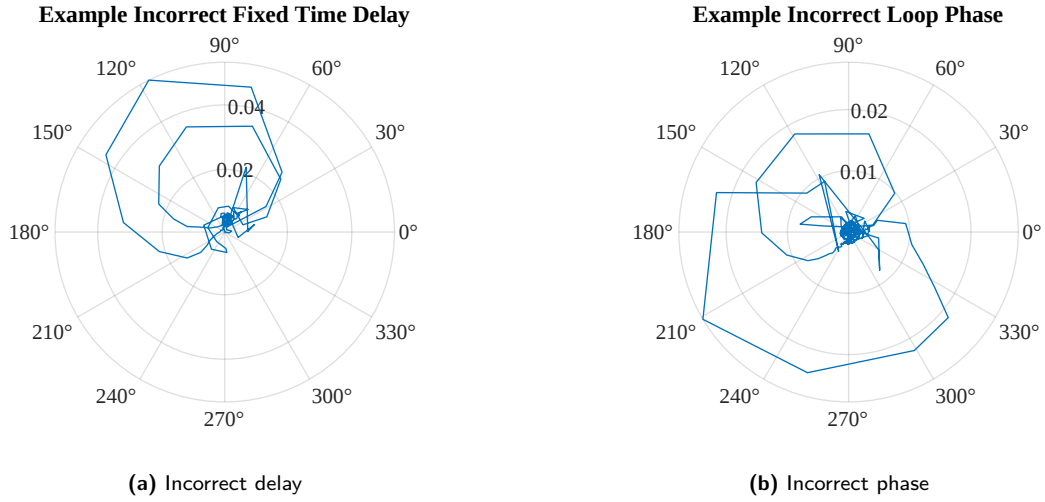


Figure 1.3: Adjustment of loop delay and feedback phase in the PSB using a VNA [50]. Left: the resonant lobes overlap but do not point towards 180°. Right: both resonant lobes deviate evenly from the target value (180°).

phase margin. An example of the performance insight obtained is shown in Fig. 1.4. In this example, the loop phase was scanned before and after the loop delay optimisation. It visually illustrates how incorrect delay (and its contribution to the phase error, see (1.1)) can result in reduced phase margin and hence sub-optimal performance of the TFB system, as assessed by measuring and evaluating beam transmission. It is worth noting that one measurement point is one machine cycle, so it is an extremely time-consuming validation process. An important point to note here is that if there is no transmission (as for example in Fig. 1.4 where the value along the y-axis dropped below 100 % for certain TFB Phase settings), the beam will be lost in the machine. This inevitably increases the radiation exposure of the accelerator components, which should always be kept as low as possible.

Since the tune in the PSB is dynamically changed during the cycle, the digital TFB system was designed with the ability to program the feedback phase along the cycle. Depending on the accuracy of the pre-calculated function, this guarantees optimal performance at any point in the cycle. Phase scans were repeated for several horizontal tunes spanning the current PSB operation working range, from $Q_H = 4.10$ to 4.40. This step made it possible to validate the correctness of the phase mapping as a function of the tune in the hardware. Excellent agreement between the measurements and the simulation was observed (see Fig. 1.5), however it took several hours of machine time to obtain all the data for this graph.

We can use modern signal processing techniques and methods to quickly and accurately measure the overall TFB performance. This allows us to optimize the TFB system, compensate for hardware imperfections, dynamically reconfigure the TFB performance through the machine cycle, provide individually tailored TFBs for different bunches, or sub-sets of bunches in the fill, and many more.

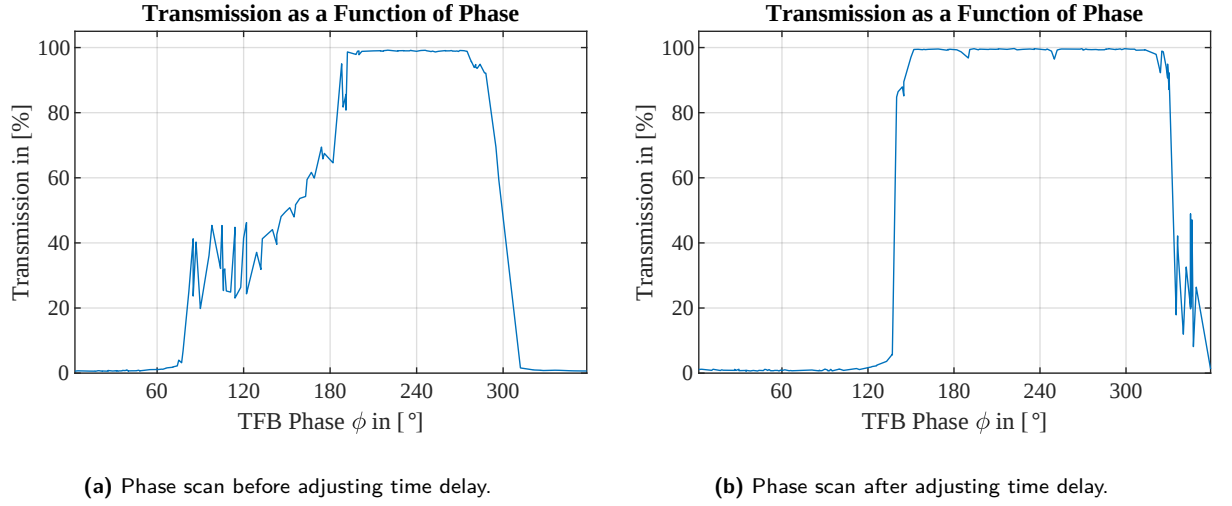


Figure 1.4: Evaluation of PSB beam transmission as a function of TFB feedback phase. Left: initial setting. Right: after loop delay adjustment with the VNA.

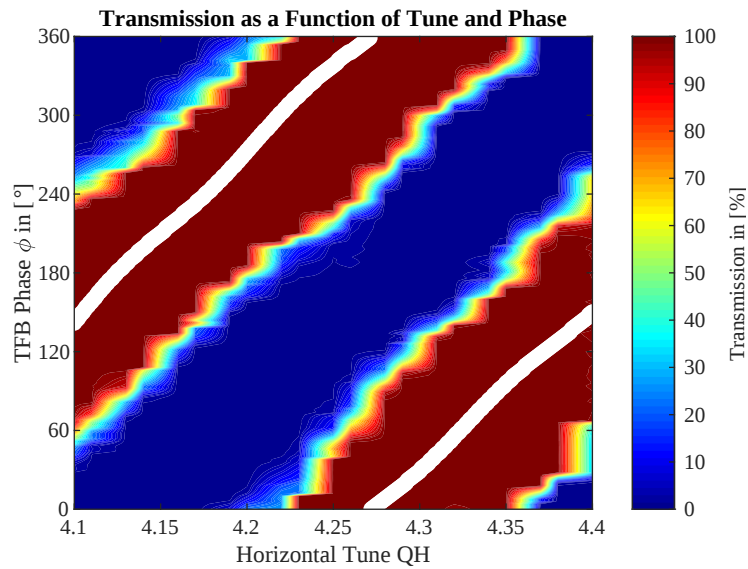


Figure 1.5: PSB transmission measurement as a function of machine tune and TFB phase setting. The white trace corresponds to the mapped horizontal tune as a function of the phase.

There is a strong need to research and introduce novel methods that will allow the TFBs to be set up in an accurate, scientific, fast, and efficient way. Novel methods, which will ideally not rely on any external instruments, but should fully utilize the potential of the TFB's digital signal processing hardware. Topics of this thesis.

1.3 Analogue and digital signal processing for TFBs

The TFBs act as a closed-loop feedback systems, taking the measurement of the instantaneous beam position as input and feeding a kicker that acts on the transverse momentum. The measured quantity (position) and the actuator action (momentum) are not of the same kind, so a conversion from position to correction kick requires some transformation. Historically, this has been achieved through various techniques [7, 29, 42, 51–53]. The sensors had to be positioned in the accelerator lattice such that the total phase shift between the sensor and the kicker provided the position to momentum conversion. However, this is not always possible. In [29, 54], one solution to this utilized two independent position sensors spaced 90° apart in the lattice. Their output signals formed in-phase and quadrature components that could be combined in an analogue domain to provide the desired vector rotation. Beneficial to this, the actuator position in the lattice is no longer constrained to a favourable phase advance position, which relaxes some machine design constraints.

With the introduction of the first generation digital technology, it became possible to use very simple digital filters to process the sensor data. In 1984, the three pioneers at CERN, Bossart, Lambert and Louverse introduced a very simple digital finite impulse response filter made out of hard-wired ECL gates, multipliers and adders. The filter was tested in the SPS [49, 55]. The demonstrator worked, but the idea was ahead of the available 8-bit technology – the resolution was not sufficient for operation in the accelerator [56]. Years later, an improved logic was implemented in a *Field Programmable Gate Array* (FPGA) [57]. The digital system made it possible to overcome some of the limitations of earlier analogue technology, such as temperature dependence, immunity to noise and interference, non-linearities, dynamic parameter reconfiguration, loss-less data transmission over long distances, and others.

State-of-the-art particle accelerators require state-of-the-art transverse feedback systems. With machines like the LHC and its injectors, machine optics change on the fly, TFB performance is critical, and feedbacks are operated at the stability limit defined by processing delay and the gain/phase margins. There is a strong need for research and adoption of novel signal processing methods that make it possible to extend the tune acceptance range, minimize processing delay to allow for higher gains or margins, design signal processing methods that allow dynamical

reconfiguration as the machine accelerates the beam through the cycle. Topics that this thesis will cover.

1.4 Extraction of valuable machine parameters from TFB data

Modern TFBs are based on powerful digital technology. The system has digital information available about the bunch by bunch, turn by turn beam position for all bunches and a history of turns, all from several independent sensors distributed in the machine (in LHC four sensors per beam per plane, 16 in total). In addition, the digital systems can synthesize virtually any signal to excite the beam using the same deflectors already used for the transverse feedback functionality.

Fully digital transverse feedback systems are a game changer. Suddenly, extremely valuable information about the accelerator and the circulating beam could be made available to the machine operators and accelerator scientists. Availability of the bunch by bunch and turn by turn position information opens completely new possibilities for the extraction and monitoring of machine parameters. Thanks to powerful, modern computing systems, these can even be extracted in real-time. With a good understanding of signal processing theory and techniques and the availability of powerful technology, we can go even further. Get the real-time data from the TFB, process it by computation-intensive algorithms and use it for various real-time feedbacks in the machine. As an example, the available data was used to demonstrate the proof-of-principle direct measurement of the Landau damping strength in LHC [22].

Tune is a critical machine parameter, precise knowledge of which is essential for accelerator operation. In high-intensity machines, where collective effects play an important role, the tune is not only a function of the magnetic lattice, but also of the beam intensity, the machine impedance, and the interaction between the beams via the wake fields. The LHC can accelerate up to 2808 bunches distributed in 3564 possible positions. Typically, the beam circulates in a form of tightly spaced bunch trains. Up to 288 bunches per train can be injected into the LHC. Additional tune shift is introduced by the beam itself, with a different value for each individual bunch in the train. The effect can be caused by beam-beam effects (so called Pacman bunches)[58, 59], by machine impedance [60, 61] or by electron cloud [62]. In order to operate machines like the LHC, it becomes important to measure the bunch by bunch tune, something unprecedented until now. The problem is even more difficult since the measurement must be accurate to a resolution of at least 10^{-3} , preferably 10^{-4} .

Tune measurement, in a regime of strong damping by an active transverse feedback system is a challenge even for the regular LHC tune measurement system called BBQ [63, 64]. Due to the

analogue way of measuring the tune by the BBQ system, it is not possible to measure the tune for individual circulating bunches. With some gating in the RF domain, an average tune value can be obtained for a group of consecutive bunches [65]. However, measuring bunch by bunch tune values by traditional RF methods is unattainable. The TFB has digital information about the transverse position of each bunch, so using the TFB data to measure and extract the tune is an attractive idea. Similar to the BBQ, even digital bunch by bunch tune measurement in a strong damping regime is very challenging, especially for FFT based algorithms (e.g. SUSSIX [66]), or curve fitting tools. There is a strong interest in researching and developing novel methods that allow extracting bunch by bunch tune information in real-time with a resolution of 10^{-3} or better.

Topics that this thesis will address.

1.5 TFB status monitoring

An important aspect of TFB operation is constant monitoring of the system status. A well-known wisdom says: complex systems break in complex ways. When operating machines such as the LHC or its injectors, complex problems are the order of the day. Typically, it is not immediately apparent what the root cause of the emerging or already existing problem is. In such situations the operations group contacts the equipment experts with a request to verify that their system is functioning well. Answering the famous operator's question *Is the damper damping?* is more difficult than it might seem.

There is a strong interest in exploring and introducing a simple, well-defined parameter, a single number, or defining a simple method (that can be automated), which makes it possible to answer this question – *Yes, the TFB is functioning well, and the damper is damping.*

A subject that is addressed by this thesis.

Chapter 2

Research objectives

In line with the analysis of the current state of the problem and the work motivation, the research objectives for this thesis are stated as follows:

Objective #1:

Identify and describe relevant parameters affecting the transverse feedback performance, such as: loop gain, feedback phase, delay, processing noise.

Research and propose signal processing techniques and analysis algorithms that allow evaluating and quantifying the identified parameters. The method should also be applicable to automatic performance verification while the machine is operated with beam.

Objective #2:

Investigate and define methods to measure and set up the key feedback parameters represented by open and closed loop gain, feedback phase, loop delay. The method should be fast (in order of machine turns) and preferably not destructive to the beam. The results should be accurate and easy to objectively interpret. The results should be usable directly for automated transverse feedback setting-up.

Research and propose required signal processing techniques and analysis algorithms to perform the TFB set-up, using exclusively the TFB system without external instruments and available observables within.

Objective #3:

Research and propose methods and required signal processing techniques to extract vital

accelerator parameters in real-time, from observables available within the transverse feedback system, at least bunch-by-bunch machine tune, damping time, injection errors, or injection kicker waveform. Investigate the feasibility of these measurements from the injection transients (or active excitation) and from passive observation of the circulating beam.

Objective #4:

Investigate the computational complexity of the proposed methods and signal processing techniques and evaluate how they could be realized for the respective accelerator (e.g. real-time processing in TFB FPGA, real-time processing in high-performance computing system, suitable only for offline processing).

Objective #5:

Research and propose advanced signal processing techniques to obtain a transverse feedback system that is more robust to variations in machine parameters, especially larger tune acceptance. Focus on FIR methods capable to compensate frequency dependent phase variations.

Chapter 3

Methods

To investigate the methods and techniques necessary to achieve Objective #1, a comprehensive system model must first be created [9, 67]. This chapter begins by breaking down the TFB into individual blocks, for which we develop detailed mathematical models. These models will be analyzed to determine their contributions to the overall TFB function, assess key parameters, identify which TFB blocks can be simplified or omitted for analysis, and define the critical blocks and parameters needed to meet the objective.

Building upon this foundational modeling, key system parameters associated with the TFB will be identified and elaborated upon within the context of controls engineering, aligning with Objective #1.

Additionally, this chapter will discuss methods for reconstructing the transverse phase space, introducing new algorithms for both spatial and temporal analysis. These methods will provide valuable insights into the system's dynamics. The exploration of transverse phase space reconstruction represents a significant contribution of this thesis, as it is essential for fulfilling Objectives #2 and #3, thereby enhancing the understanding of the field.

Subsequently, the focus will shift to the extraction of TFB parameters, including gain, phase, and delay, alongside accelerator parameters such as bunch-by-bunch tune and damping time. This extraction is made possible by the data obtained from the reconstructed transverse phase space. The sensitivity of the algorithm to noise will also be evaluated as part of Objective #1, outlining further requirements for the data quality of the available observables from the TFB.

Finally, this chapter will conclude with an assessment of the computational complexity associated with the methodologies, in line with Objective #4.

3.1 System modeling

The aim is to obtain a simplified representation of the overall TFB system and all of its components. The simplified model makes it possible to derive stability constraints and to identify a controller that ensures that the dynamic system and the overall system function in a stable manner.

Figure 3.1 illustrates the situation in a concise block diagram. Considering the use of an embedded digital controller suggests the introduction of two domains, one of which is the continuous-time domain covering analogue systems and the beam model in the Laplace domain. On the other hand, all operations performed digitally are best represented in the z -domain, or equivalently, the discrete-time domain. Transitions between domains are included in the sensor block and the actuator block, respectively.

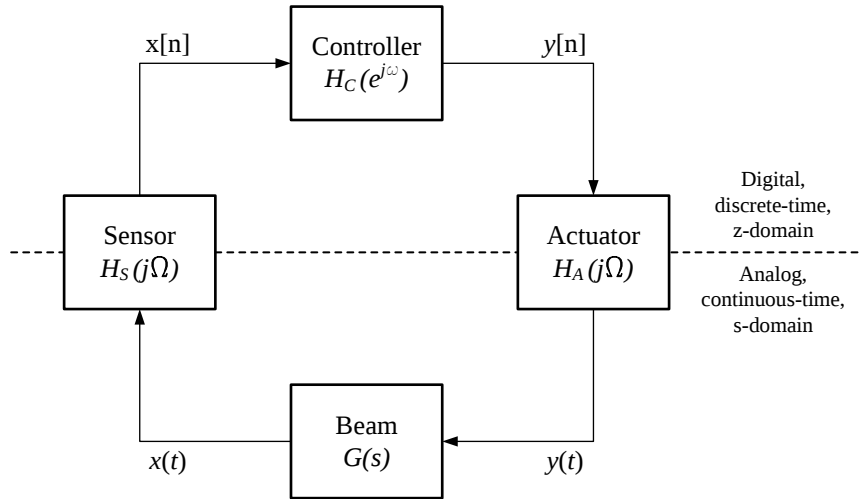


Figure 3.1: Feedback loop

The digital controller calculates the necessary control signal from the sensor input and feeds the actuator that manipulates the beam. Ideally, the sensor does not change the information that it collects. It exhibits a constant gain within the frequency band of interest, along with a constant signal delay that is independent of frequency. The transverse beam motions $x(t)$ are monitored in such a way that the sensor's output represents the position of each individual bunch, and is readily converted into a discrete-time sequence $x[n]$. This data stream is fed into the digital controller to calculate a correction signal $y[n]$. The actuator, in turn, converts the information into a continuous-time deflection signal $y(t)$, which acts back on the beam. Just like the ideal sensor, the ideal actuator also has a constant gain and a linear phase over the desired frequency range.

In the following it is shown that the beam model $G(s)$ can also be modeled as a discrete-time system $G(z)$, a notation best suited to signal processing techniques. This is based on the assumption that the sensor and the actuator can be simplified to a pure continues-to-discrete and discrete-to-continuous converter – this will be addressed in the following sections.

3.1.1 Beam representation in z-domain

Although the beam is essentially an ensemble of discrete particles, its ‘macroscopic properties’—or directly observable phenomena—are best described in the continuous-time domain. However, the beam moves close to the speed of light, while observations, for example with beam position monitors, are stationary (ignoring ground movements). Those position monitors basically ‘sample’ the passing beam, and thus generate a discrete-time representation. Therefore, the parameters of interest are optimally described using the concept of discrete-time signal processing.

Starting with the equation of motion from equation (??),

$$x(s) = A\sqrt{\beta(s)} \cos(\psi(s) + \phi). \quad (3.1)$$

Here $\beta(s)$ is the optics β -function, a location-dependent parameter that accounts for the magnetic guidance field at a longitudinal coordinate s . The magnetic field also defines the oscillation phase, $\psi(s)$. Initial conditions are given by the peak oscillation amplitude A and an initial phase ϕ . In the following notations a dependence on the longitudinal coordinate s is omitted for simplicity.

The first derivative of (3.1) with respect to the longitudinal coordinate follows directly as

$$\frac{dx}{ds} \equiv x'(s) = -A \frac{1}{\sqrt{\beta}} [\alpha \cos(\psi + \phi) + \sin(\psi + \phi)]. \quad (3.2)$$

Here x' is the slope of the particle trajectory along the longitudinal direction. The parameter α is another Twiss optics function describing the magnetic lattice.

The equations (3.1) and (3.2) describe the particle motion through the magnetic guidance field. Rewriting them as a vector, $\tilde{\mathbf{x}}$, one gets,

$$\tilde{\mathbf{x}} = \begin{pmatrix} x \\ x' \end{pmatrix}. \quad (3.3)$$

The dependency of the Twiss parameters can be eliminated by applying a linear transformation. The linear operator, denoted as Λ , is a function of the azimuthal location s that maps the vector $\tilde{\mathbf{x}}$ to the state vector $\mathbf{x}$:

$$\tilde{\mathbf{x}} \xrightarrow{\Lambda(s)} \mathbf{x}, \quad (3.4)$$

This mapping provides a representation of a state vector that is independent of local amplitude functions. With the operator of the form

$$\Lambda(s) = \frac{1}{\sqrt{\beta}} \begin{pmatrix} 1 & 0 \\ -\alpha & -1 \end{pmatrix}, \quad (3.5)$$

the state vector therefore simplifies to

$$\mathbf{x} = A \begin{pmatrix} \cos(\psi + \phi) \\ \sin(\psi + \phi) \end{pmatrix}. \quad (3.6)$$

Considering the trigonometric form of (3.6), this suggests introducing a complex notation for representing $\mathbf{x}$ in two-dimensional space. Equivalently to,

$$x = A(\cos \psi + j \sin \psi) = Ae^{j\psi}, \quad (3.7)$$

where the initial conditions of the transverse oscillations, the oscillation amplitude A and the initial phase ϕ , have been combined in a complex phase vector (phasor¹),

$$A = |A| e^{j\phi}. \quad (3.8)$$

If the complex oscillation amplitude at a location s_1 is known, i.e.

$$x_1 = Ae^{j\psi_1}, \quad (3.9)$$

then the oscillation condition at any other point s_2 follows from

$$x_2 = Ae^{j\psi_2} = Ae^{j(\psi_1 + \Phi_{21})}. \quad (3.10)$$

Here the machine-dependent phase advance Φ_{21} between the two locations, s_1 and s_2 has already been found in Chapter ???. It is given by the definite integral

$$\Phi_{21} = \int_{s_1}^{s_2} \frac{d\sigma}{\beta(\sigma)}, \quad (3.11)$$

which rewrites with (??) to the difference in phase advances

$$\Phi_{21} = \psi(s_2) - \psi(s_1). \quad (3.12)$$

¹Throughout this book a phasor shall refer to a complex constant, i.e. $C = |C| e^{j\phi}$.

The values for the phase advances can be obtained directly from optics simulations or extracted from dedicated measurements.

Since a particle exhibits an exact number of Q oscillations during a complete turn, it follows from (??) for the phase advance over one turn,

$$\Phi_{21} = 2\pi Q. \quad (3.13)$$

Inserting (3.13) into (3.10) and including the constant phase value ψ_1 in the initial phase leads to a representation for the state vector and the n -th turn,

$$x[n] = Ae^{j2\pi Qn} \quad n \geq 0. \quad (3.14)$$

The previous equation describes a discrete-time complex exponential sequence. It represents the sampled transverse beam oscillations observed at a single location and for every turn.

Since the absolute value of the complex exponential function in (3.14) is unity, the sequence is stable in magnitude, and its initial oscillation amplitude $|A|$ is preserved (see Figure 3.2).

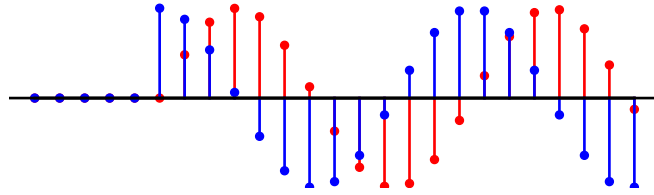


Figure 3.2: A transverse displacement (blue) converts into slope (red) with a phase lag of $\pi/2$.

A more general form of this sequence is described in [68, Chapter x, Equation(y.z)] as

$$x[n] = A\alpha^n u[n], \quad (3.15)$$

where A is a phasor (see (3.8)) and with a complex base, α ,

$$\alpha = |\alpha| e^{j\omega_0}. \quad (3.16)$$

In (3.15) the unit step sequence $u[n]$ follows from

$$u[n] = \begin{cases} 1, & n \geq 0 \\ 0, & n < 0 \end{cases} \quad (3.17)$$

to take into account that no oscillations exist for $n < 0$.

The equivalent first-order difference equation of (3.15) is given by the recursion formula

$$x[n] = \alpha x[n-1] \quad n > 0. \quad (3.18)$$

Introducing the z -transform [68], defined by the $\mathcal{Z}\{\cdot\}$ -operator¹,

$$\mathcal{Z}\{x[n]\} = \sum_{n=-\infty}^{\infty} x[n] z^{-n} = X(z). \quad (3.19)$$

and applying it to (3.15) yields

$$X(z) = \mathcal{Z}\{x[n]\} = A \sum_{n=0}^{\infty} |\alpha|^n e^{j\omega_0 n} z^{-n}. \quad (3.20)$$

The preceding equation requires the definition of a region of convergence (ROC) for which the sum is finite, i.e. the sequence is absolute summable. The necessary condition is therefore

$$\sum_{n=0}^{\infty} |\alpha z^{-1}|^n < \infty. \quad (3.21)$$

This inequality is only fulfilled for values of $|z| > |\alpha|$. If one restricts the evaluation of (3.20) to the region of convergence, it follows with the general solution of a power series that the infinite sum can be expressed in closed form as

$$X(z) = A \frac{1}{1 - \alpha z^{-1}} \quad |z| > |\alpha|. \quad (3.22)$$

The properties of this remarkable compact equation will be explored in more detail below. The rational function has a single pole at $z = \alpha$ (see Figure 3.3), which corresponds to the fact that the time sequence is complex-valued: the convention used in (3.7) and (3.3) attributes the real part of $x[n]$ as the transverse displacement and the imaginary part as the slope.

The amplitude value A in (3.22) is a linear scaling factor, while α characterizes the behaviour of the oscillation. The value of $|A|$ defines the magnitude of the oscillation amplitude for $n = 0$. The complex factor $e^{j\phi}$ determines the initial ratio between displacement versus slope. For example, a phase value of $\phi = 0$ starts the oscillations with maximum displacement. On the other hand, if the angle is equal to $\phi = \pi/2$, then the trajectory has no offset, but is maximally inclined.

Since $|\alpha|^n$ in (3.20) is an exponential sequence, it is the base value $|\alpha|$ that defines the resulting sequence. That is, if $|\alpha| > 1$ then the sequence values increase as n increases. If

¹Here the bilateral transform has been chosen, which eventually leads to the unilateral z -transform when the signals are causal.

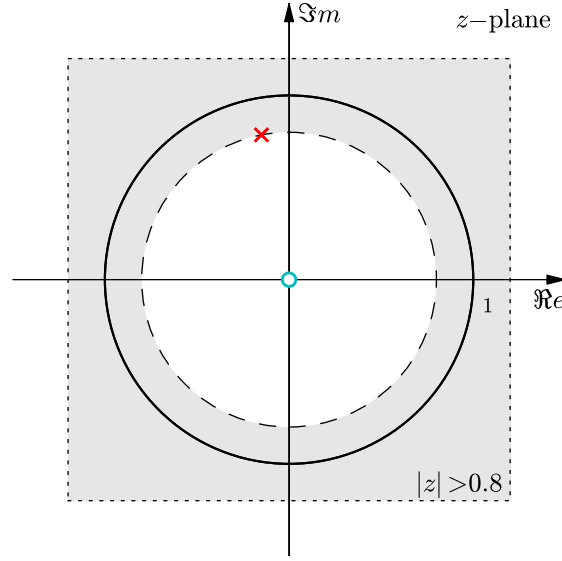


Figure 3.3: Pole-zero plot and ROC for (3.22) in the complex z -plane. The function has a single pole, denoted by 'x', and a zero at the origin, denoted by 'o'. The dotted circle represents the unit circle, $z = e^{j\omega}$.

$0 < |\alpha| < 1$, then the sequence values decrease with increasing n . The oscillation remains stable in the case $|\alpha| = 1$.

The oscillation frequency is determined by the argument of α , which is defined as ω_0 in (3.16). Analogously to (3.14), it is a complex exponential sequence that oscillates with frequency $\omega_0 = 2\pi Q$ as n increases.

The sequence $x[n]$ completely describes the transverse state for each sample n . The state variables x and x' thereby are represented by the real and imaginary parts. The beam propagates through the magnetic guidance field of the accelerator, which applies focusing forces to prevent the beam from diverging. This in turn causes an oscillation that continuously converts transverse displacement into slope and vice versa (i.e. the trajectories of a free-running undamped system are circles). The previous derivation showed that the single pole in the z -plane characterises a complex sequence $x[n]$. If the roots of the denominator in (3.22) consisted of a pair of conjugate complex poles, then the resulting sequence would be real-valued, i.e. the imaginary part would always be zero. However, the transverse position still oscillates which is obviously a non-physical behaviour.

Furthermore, transverse deflecting devices act solely on the slope of a particle's trajectory (trajectories must be continuous at all times; a stepwise displacement at an infinitesimal short longitudinal distance requires either infinite energy—or transverse teleportation). Accordingly, all manipulations that also represent a physical meaning must be made for the imaginary part only.

A note on the convention of the principal coordinate system (see Chapter ??, page ??), a positive displacement commutes into a negative slope (positive angular frequency in clockwise

direction). However, by defining a linear mapping as in (3.5), the direction of rotation also changes. This leads to the conclusion that – for the signal processing part – a positive displacement commutes to a positive slope. This conforms to the general convention in signal processing and engineering that a positive angular frequency rotates in counter-clockwise direction.

With the above, and to get an input-output relationship for a simplified beam model, let us now revisit the rational function $X(z)$ in (3.22). It has a single complex-valued pole at $z = \alpha$, which corresponds to the fact that the sequence $x[n]$ is also complex-valued. It represents the simplest form of an Infinite Impulse Response filter (IIR), as outlined in Figure 3.4. Thereby, the convention used for Eq. (3.3) attributes the real part of $x[n]$ as transverse displacement, $y = \Re\{x\}$, and the imaginary part as the trajectory's slope. Accordingly, in Figure 3.4 the beam position monitor (or pick-up) extracts transverse displacement as $y[n] = \Re\{x[n]\}$.

The action of a kicker only changes the particle's slope. Consequently, in Fig. 3.4 the real-valued input sequence $\theta[n]$ is first multiplied by the imaginary unit $j = \sqrt{-1}$ and subsequently added to the complex-valued sequence $x[n]$.

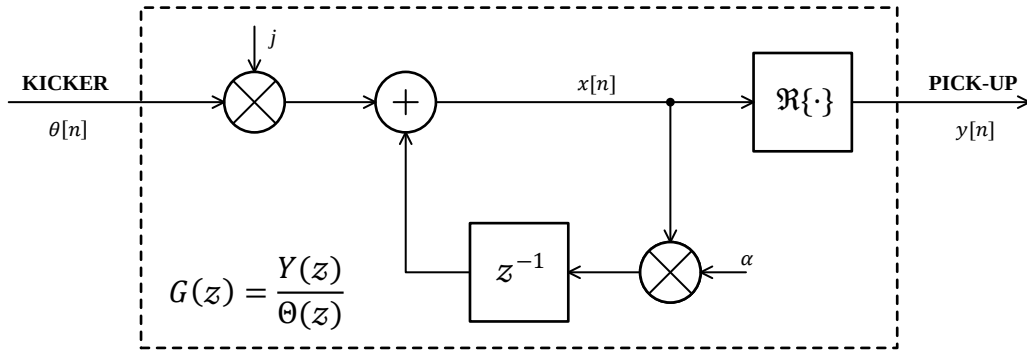


Figure 3.4: Simple beam model in z -domain.

The overall beam transfer function $G(z)$ can therefore be expressed as

$$G(z) = \frac{Y(z)}{\Theta(z)} = j \frac{1}{2} \left(\frac{1}{1 - \alpha z^{-1}} - \frac{1}{1 - \alpha^* z^{-1}} \right). \quad (3.23)$$

Here, α and α^* are the two conjugate complex poles of $G(z)$. It is worth noting that the second pole seen at the output, $Y(z) = G(z)X(z)$, is the result of the pick-up and its ability to only detect transverse position.

Equation (3.23) can be expanded and rewritten as

$$G(z) = \frac{r \sin \omega_0 z^{-1}}{1 - 2r \cos \omega_0 z^{-1} + r^2 z^{-2}}, \quad (3.24)$$

which makes it evident that due to the term z^{-1} in the numerator the output sequence is readily delayed by one sample, corresponding to the fact that a response to a transverse deflection at a particular longitudinal position is visible only after one turn.

In Eq. (3.24) the parameter r determines whether the oscillation at frequency ω_0 is stable ($|r| < 1$), steady ($|r| = 1$), or unstable ($|r| > 1$).

Taking into account an arbitrary phase shift ϕ_{PU} between the kicker and the pick-up, i.e. by extending the pick-up output such that $y[n] = \Re\{x[n] \cdot e^{j\phi_{PU}}\}$ one obtains more generally as beam transfer function

$$G(z, \phi_{PU}) = \frac{r \sin(\omega_0 + \phi_{PU}) z^{-1} - r^2 \sin \phi_{PU} z^{-2}}{1 - 2r \cos \omega_0 z^{-1} + r^2 z^{-2}}. \quad (3.25)$$

As can be seen from Eq. (3.25) the introduction of a betatron phase advance ϕ_{PU} between pick-up and kicker has no impact on the position of the poles (the denominator is unaltered). In fact the required phase shift is established solely by an additional zero in the numerator, moving on the real axis of the z -plane as the phase angle changes.

3.1.2 Sensor model

This section is about identifying an analytical model for a transfer function between the transverse beam position as input to a sensor and the generated output. The transverse feedback systems of the LHC and the SPS are designed to measure bunch-by-bunch transverse displacements and damp oscillatory movements by means of fast electric field kickers. In order to detect the time-varying beam position the signals of individual bunches are processed in analog and digital [69, 70], generating one position reading per bunch per turn.

The design criterion for position signal processing is to have one position reading per bunch, that is, one sample spaced every T_s .

Independent treatment of bunches does require no cross-talk between adjacent bunches, a parameter known as inter-symbol interference (ISI). This restriction limits the continuous-time response of the sensor's analog system, $g(t)$, to zero at adjacent sampling points, i.e.,

$$g(kT_s) = 0; \quad \forall k \in \mathbb{R}^*. \quad (3.26)$$

If this condition is fulfilled then each bunch position can be treated independently by the feedback control as there is no coupling term added in the analog processing chain. At this point it is worth noting that the time limit on the impulse response, as required by (3.26), implies that the frequency response of the entire analog system must extend beyond the sample repetition rate $f_s = 1/T_s$.

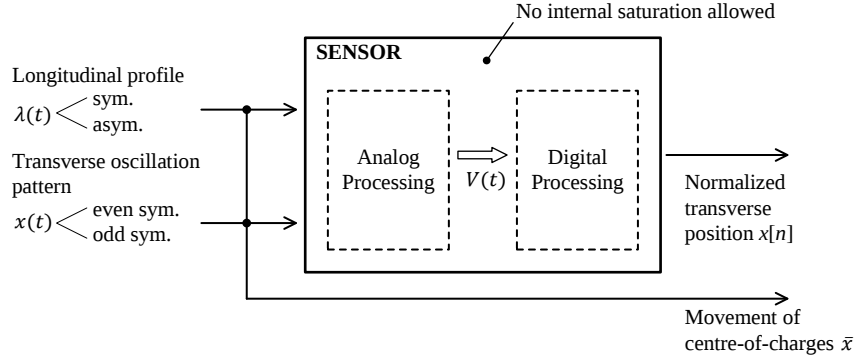


Figure 3.5: Evaluation of the TFB sensor performance.

In the following we analytically evaluate the performance of the sensor's beam position signal processing scheme for normalized longitudinal bunch profiles $\lambda(t)$ and transverse oscillation patterns $x(t)$ as test inputs (see Figure 3.5).

For comparison, the true motion of the center-of-charges $\bar{x}$, given as

$$\bar{x} = \int x(t)\lambda(t) dt, \quad (3.27)$$

for different excitation frequencies is tested against the digital representation of the beam normalized transverse position $x[n]$, as calculated by the LHC TFB beam position sensor.

The block diagram in Figure 3.6 outlines the signal processing chain of the LHC beam position measurement hardware. Beam-induced signals in a pickup go through an analog processing chain before being synchronously converted to digital in analog-to-digital-converters (ADC). An FPGA calculates a normalized position for each individual bunch from the data streams. This value is independent of the intensity per bunch or the longitudinal bunch shape.

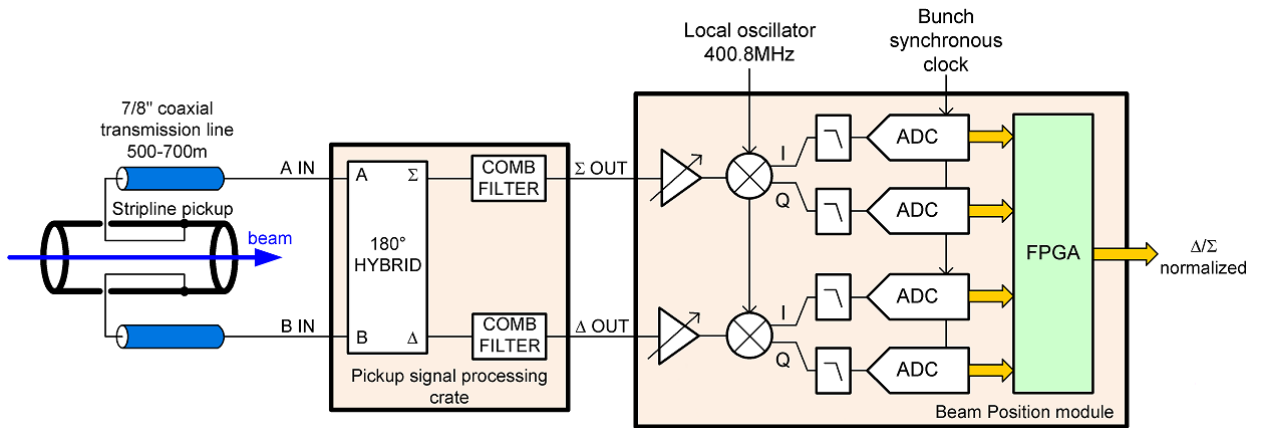


Figure 3.6: LHC beam position hardware signal processing scheme for Run I and Run II (taken from [69]).

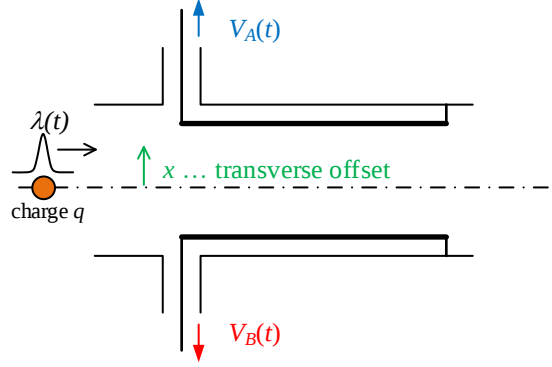


Figure 3.7: BPM coupler type pick-up with constant coupling.

Analog processing scheme

The electromagnetic field generated by a circulating bunch with normalized longitudinal profile $\lambda(t)$ and total charge q interfaces with a stripline type beam position monitor (BPM), thereby inducing a signal into two opposing electrodes (denoted A and B), whose amplitude depends on the transverse position $x(t)$ with respect to the vacuum chamber, and the pick-up geometry d_x (linear approximation for small amplitudes). See Figure 3.7 for a simplified graphical representation. The mechanical design of the stripline electrodes achieves a characteristic impedance of 50Ω and no matching network is needed. The BPM output voltage follows from,

$$V_{A,B}(t) = Z_T \int_{-\infty}^t \left(1 \pm \frac{x(\tau)}{d_x}\right) \cdot q\lambda(\tau) \cdot h_{\text{BPM}}(t - \tau) d\tau, \quad (3.28)$$

with Z_T as the transfer impedance, and $h_{\text{BPM}}(t)$ the impulse response of the BPM.

Since the BPM for the configuration of the LHC TFB is short-circuited at the downstream end of the electrode, the beam signal induced at the upstream end is eventually completely reflected. The reverse signal returns after the roundtrip time $T_0 = 2L/c$ with negative polarity at the upstream port. The resulting impulse response of the BPM (assuming $v = c$) therefore follows as

$$h_{\text{BPM}}(t) = \delta\left(t + \frac{T_0}{2}\right) - \delta\left(t - \frac{T_0}{2}\right). \quad (3.29)$$

Here, $\delta(t)$ denotes the Dirac-Delta distribution which has the well-known properties, $\delta(t) = 0$ for $t \neq 0$, and $\int_t \delta(\tau) d\tau = 1$.

Note that (3.28) denotes a convolution integral of the longitudinal bunch profile with the pick-up response. The position information is encoded in the signal amplitude, which is AM modulated, with a strong common signal.

The peak voltages of the two electrodes can easily reach up to 400 V in the LHC for full intensity beam. This voltage is sufficient to transmit signals from the beam line in the underground

tunnel to the surface electronics using low-loss coaxial transmission lines of identical length. The transmission line attenuates the raw pick-up signals to levels acceptable to the hybrid and adds a dispersion to the pulse response, represented by $h_{\text{COAX}}(t)$.

The first element at the surface is a 180° hybrid. It combines the transmitted signals $\bar{V}_A$ and $\bar{V}_B$ into a sum signal Σ , which is common to both pickup electrodes, and it generates the difference or Δ -signal. The sum signal represents the longitudinal profile of the beam, i.e. the bunch shape and the number of charges, while the delta signal contains additional information about the transverse position.

Assuming an ideal hybrid, i.e. no crosstalk between the outputs, then

$$V_\Sigma(t) = \frac{1}{\sqrt{2}} [\bar{V}_A(t) + \bar{V}_B(t)] , \quad (3.30)$$

$$V_\Delta(t) = \frac{1}{\sqrt{2}} [\bar{V}_A(t) - \bar{V}_B(t)] . \quad (3.31)$$

A special type of bandpass filter, called a comb filter, shapes both the sum and the delta signal in the time domain into a well-defined wavelet [69]. The filter response is designed for a time-limited rectangular window of less than 25 ns, shorter than the nominal bunch spacing, to ensure no mixing between adjacent bunch signals. These filters have a center frequency of 400.8 MHz, which corresponds to the LHC RF frequency.

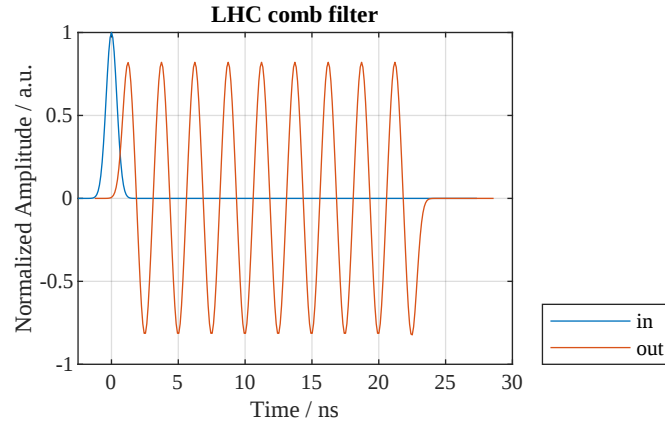


Figure 3.8: Bandpass filter response

The bandpass filter output (denoted with a tilde), applied for the Σ signal in (3.30) by inserting Eq. (3.28), results from

$$\tilde{V}_\Sigma(t) = q\lambda(t) * h_{\text{PU}}(t), \quad (3.32)$$

where

$$h_{\text{PU}}(t) = \sqrt{2}Z_T \cdot h_{\text{BPM}}(t) * h_{\text{COAX}}(t) * h_{\text{BP}}(t). \quad (3.33)$$

Equation (3.33) represents the cascade or convolution (here and hereafter referred to with asterisk notation) of impulse responses in the time domain, including the beam transfer impedance, the signal gain by $\sqrt{2}$ in the hybrid, and passive linear elements that shape the response in time and frequency domain.

Similarly, the Δ signal output follows from Eq. (3.31) in combination with Eq. (3.28) as,

$$\tilde{V}_{\Delta}(t) = \left(\frac{x(t)}{d_x} \cdot q\lambda(t) \right) * h_{\text{PU}}(t). \quad (3.34)$$

These equations (3.32) and (3.34) describe the underlying formalism in the time domain, the effects of which are visible in the frequency domain. Namely, the convolution in the time domain leads to a multiplication in the frequency domain, or

$$\tilde{V}_{\Sigma}(j\omega) = q\Lambda(j\omega) \cdot H_{\text{PU}}(j\omega). \quad (3.35)$$

On the other hand, multiplication in the time domain as within (3.34) leads to a convolution in frequency domain. Therefore,

$$\tilde{V}_{\Delta}(j\omega) = \left(\frac{X(j\omega)}{d_x} * q\Lambda(j\omega) \right) \cdot H_{\text{PU}}(j\omega). \quad (3.36)$$

For the case of a sinusoidal excitation with $X(j\omega) = \delta(\pm\omega_x)$, the previous equation states that a transverse oscillation causes a shift in the spectrum of the longitudinal bunch profile to the carrier frequencies at $\pm\omega_x$,

$$\tilde{V}_{\Delta}(j\omega) = \frac{1}{d_x} q\Lambda [j(\omega \pm \omega_x)] \cdot H_{\text{PU}}(j\omega). \quad (3.37)$$

As shown in Figure 3.6, the Beam Position Module uses a set of mixers to demodulate the bandpass filtered signals into in-phase and quadrature components (I/Q pairs for Δ and Σ). This is followed by optimized Gaussian low-pass filters, which suppress image frequencies and shape the system response to minimize output ripples.

The baseband response of the in-phase component, which has even symmetry, is obtained by multiplying by $c(t) = \cos(\omega_{\text{LO}}t)$. In contrast, the quadrature component, which has odd symmetry, is obtained by multiplying by $s(t) = \sin(\omega_{\text{LO}}t)$.

Therefore, from (3.32) we get for the Σ -signal after low-pass filtering:

$$\begin{aligned} I_{\Sigma}(t) &= k_{\Sigma} [q\lambda(t) \cdot c(t)] * g(t), \\ Q_{\Sigma}(t) &= k_{\Sigma} [q\lambda(t) \cdot s(t)] * g(t), \end{aligned} \quad (3.38)$$

where signal level adjustments and other coefficients are combined into a single scalar, k_{Σ} , and with

$$g(t) = [h_{\text{PU}}(t) \cdot c(t)] * h_{\text{LP}}(t). \quad (3.39)$$

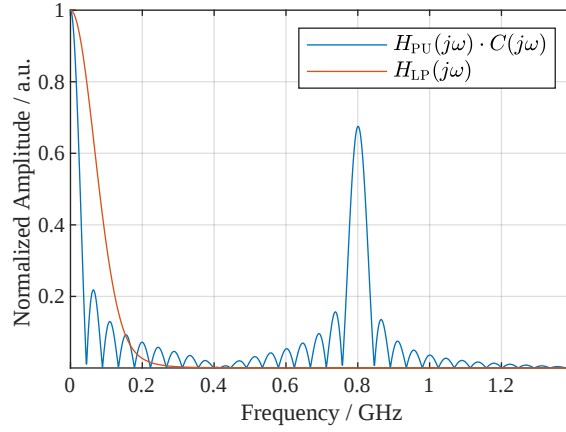
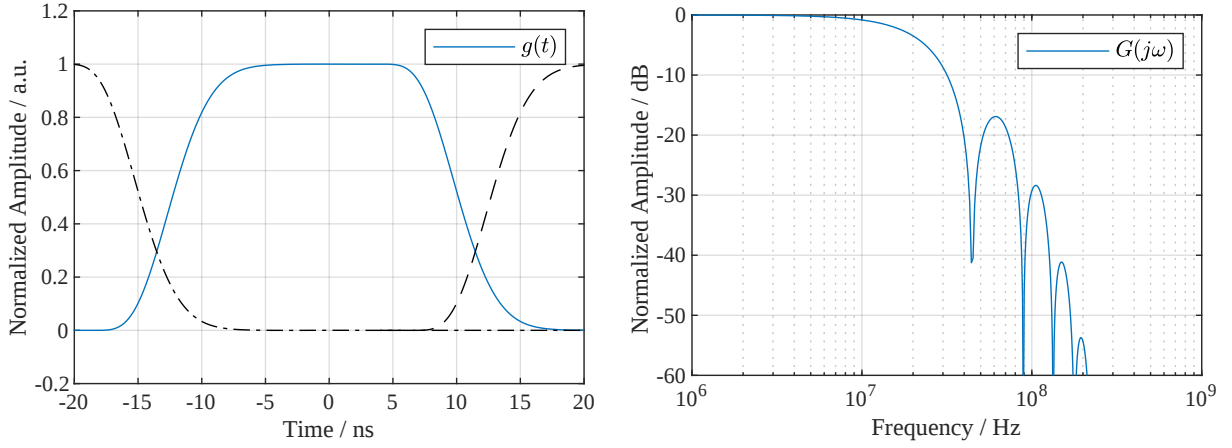


Figure 3.9: Frequency response of $h_{PU}(t) \cdot c(t)$ and lowpass filter $h_{LP}(t)$.



(a) Baseband impulse response $g(t)$.

(b) Baseband transmission response $G(j\omega)$.

Figure 3.10: Sensor response function. Left: time domain. Right: frequency domain.

Equation (3.39) states that the response function of (3.33) is demodulated into baseband and then lowpass filtered by $h_{LP}(t)$. A graphical representation of this relationship in frequency domain is shown in Figure 3.9.

At this point it is worth noting that the shape of the baseband response of (3.38) is completely defined by $g(t)$ and only its amplitude is a function of the demodulated longitudinal profile.

An assessment of the sensor response function $g(t)$ in both the time and frequency domains is presented in Figure 3.10.

Similarly, I/Q demodulation of the bandpass filtered Δ signal provided by (3.34) gives the

following:

$$\begin{aligned} I_{\Delta}(t) &= k_{\Delta} \left\{ \left(\frac{x(t)}{d_x} \cdot q\lambda(t) \right) \cdot c(t) \right\} * g(t), \\ Q_{\Delta}(t) &= k_{\Delta} \left\{ \left(\frac{x(t)}{d_x} \cdot q\lambda(t) \right) \cdot s(t) \right\} * g(t). \end{aligned} \quad (3.40)$$

Here the order of multiplication is important: (1) transverse position modulation $x(t)$, (2) demodulation with $c(t)$ or $s(t)$.

Similar to the baseband response defined in (3.38), the shape of the baseband response in (3.40) is determined solely by $g(t)$. However, in this case, the amplitude also depends on the excitation frequency and the longitudinal profile.

Digital position calculation

A total of twelve beam-synchronously clocked analogue to digital converters sample the I/Q pairs and provide a digitized sample per bunch and signal[70].

The normalized bunch position is given by taking the ratio of the Δ -signal to the Σ -signal, $X_N = \Delta/\Sigma$, which is independent of the intensity per-bunch. A more elegant way was found by expanding the ratio mathematically with the conjugate complex Σ^* ,

$$X_N = \frac{\Delta \Sigma^*}{\Sigma \Sigma^*} = \frac{\Delta \cdot \Sigma^*}{|\Sigma|^2}. \quad (3.41)$$

By introducing the two phasors, $\Delta = A \cdot e^{j\alpha}$ and $\Sigma = B \cdot e^{j\beta}$,

$$\begin{aligned} \Delta &= A \cos \alpha + j A \sin \alpha \doteq I_{\Delta} + j Q_{\Delta}, \\ \Sigma &= B \cos \beta + j B \sin \beta \doteq I_{\Sigma} + j Q_{\Sigma}, \end{aligned} \quad (3.42)$$

we rewrite (3.41) in I/Q components provided by the sampling,

$$X_N = \frac{I_{\Delta} I_{\Sigma} + Q_{\Delta} Q_{\Sigma}}{I_{\Sigma}^2 + Q_{\Sigma}^2} + j \frac{Q_{\Delta} I_{\Sigma} - I_{\Delta} Q_{\Sigma}}{I_{\Sigma}^2 + Q_{\Sigma}^2}. \quad (3.43)$$

For perfect alignment of the two phasors (i.e. $\alpha - \beta = 0$), the first term maximizes in (3.43). Only the real part of X_N is used as position input in the TFB, while the imaginary part provides an indication of head-tail activities and asymmetries in the longitudinal bunch profile.

Simulation Model

Due to the sampling of the continuous-time signals, where only one value is selected, it can be shown that the convolutions in (3.38) and (3.40) can be simplified to definite integrals. Consequently, the described analytical model can be further refined into a more practical implementation that is essentially independent of hardware parameters:

1. The time-varying transverse position signal across a bunch and the longitudinal beam profile are multiplied by two fixed frequency signals in quadrature,

$$\begin{aligned} c(t) &= \cos(\omega_0 t), \\ s(t) &= \sin(\omega_0 t), \end{aligned} \tag{3.44}$$

where $\omega_0/(2\pi) = 400.8$ MHz for the case of the LHC TFB.

2. The longitudinal profile is demodulated to the baseband as

$$\begin{aligned} \hat{I}_\Sigma(t) &= \int c(t)\lambda(t) dt, \\ \hat{Q}_\Sigma(t) &= \int s(t)\lambda(t) dt. \end{aligned} \tag{3.45}$$

3. With the delta signal, the longitudinal profile is first modulated with the position signal and then demodulated into baseband, as indicated by

$$\begin{aligned} \hat{I}_\Delta(t) &= \int c(t)x(t)\lambda(t) dt, \\ \hat{Q}_\Delta(t) &= \int s(t)x(t)\lambda(t) dt. \end{aligned} \tag{3.46}$$

4. Finally, the normalization algorithm implemented in the LHC TFB follows from,

$$x_N = \frac{\hat{I}_\Delta \hat{I}_\Sigma + \hat{Q}_\Delta \hat{Q}_\Sigma}{\left(\hat{I}_\Sigma\right)^2 + \left(\hat{Q}_\Sigma\right)^2}. \tag{3.47}$$

3.1.3 TFB controller

In transverse feedback systems, a phase adjustment is typically necessary to convert a beam position signal from a pick-up into a momentum correction signal used by a transverse kicker [7, 29, 42, 51–53]. In larger synchrotrons, pick-ups and kickers can often be positioned such that the betatron phase advance between them allows the signal to be directly applied for feedback without further phase adjustments. However, these optimal locations are not always available for installing a dedicated monitor, and the required phase advance may change in machines with cycle-dependent optics.

The following analysis aims on identifying potential solutions for transverse feedback phase adjustments using short *finite impulse response* (FIR) digital filters and one or more pick-ups.

The ultimate goal could be stated as follows: determine the slope of a particle's trajectory at the position of the kicker, to be able to counteract oscillations by correcting its trajectory (i.e. the transverse momentum p_y) on a turn-by-turn basis.

Given that — at the time of writing — there is no technique known which allows to directly measure transverse momentum, it requires an indirect method to obtain the slope via position measurements.

By recalling that a pick-up measures the real part (see Figure 3.4) it becomes obvious that if the sequence is phase rotated, by -90° or $-j$, then the corresponding slope is returned as position, y_p , seen by the pick-up:

$$y_p = \Re\{-jx\} = \Re\{-jy + y'\} = y' . \quad (3.48)$$

This procedure allows for two possible interpretations to realize the phase rotation: (a) Spatial phase shift, and (b) Temporal phase shift.

Spatial phase shift

Technically speaking, equation (3.48) means nothing else than to physically place a pick-up at betatron phase advance -90° with respect to the kicker. This is the simplest form of a transverse feedback. The correct phase shift required between the position measurement and application of the correction kick can be obtained by integration into properly selected positions in the accelerator lattice. However, such a scheme makes the optics design, TFB and accelerator operation complicated as there is no flexibility in any of the parameters.

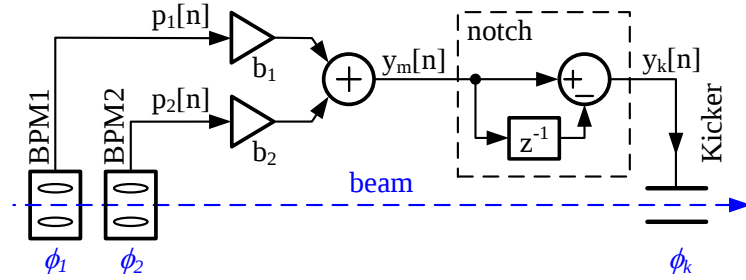


Figure 3.11: TFB signal processing using two pickups spaced exactly by $\pi/2$ (or close to) betatron phase advance. Sampling is once per turn per bunch passage, the structure is implemented for every individual bunch.

The problem can be overcome by using two beam pickups, which are conveniently placed in the lattice to have an ideal $\pi/2$ betatron phase advance between them. The two orthogonal components can be used to rotate the measured position vector by any phase by simple multiplication as illustrated in Fig. 3.11, often referenced to as *Pick-up Vector Sum*:

$$y_k[n] = p_1[n]b_1 + p_2[n]b_2 = p_1[n] \cos \varphi + p_2[n] \sin \varphi , \quad (3.49)$$

where φ is the required phase rotation angle.

For the combination of two pick-up signals that have a phase advance different than 90° a more general solution has been already formulated in Ref. [53], as *Pick-up Vector Sum*. As detailed therein, the two pick-up mixing coefficients follow from

$$b_{1,2} = -\frac{1}{2} \left(\frac{\cos(\Delta\phi_{Qkm})}{\cos(\Delta\phi/2)} \mp \frac{\sin(\Delta\phi_{Qkm})}{\sin(\Delta\phi/2)} \right), \quad (3.50)$$

where $\Delta\phi = \phi_2 - \phi_1$ describes the phase advance between the two pick-ups, and with

$$\Delta\phi_{Qkm} = -3\pi Q_f + \phi_k - \frac{\phi_2 + \phi_1}{2}. \quad (3.51)$$

The fractional tune is denoted as Q_f , and ϕ_1 , ϕ_2 , and ϕ_k are the betatron phase advances at pick-up and kicker locations with respect to some fixed reference. Equation (3.51) is readily taking into account a one-turn delay and the phase shift of the notch filter.

Temporal phase shift

During one complete revolution a particle exhibits a precise number of oscillations, thus if the fractional tune Q_f is 0.25 then a phase rotation of 90° is achieved between consecutive turns. By reconsidering (3.48) we can exploit this as

$$y_p[n] = \Re\{jx[n-1]\} = -y'[n-1], \quad (3.52)$$

which states that the position y_p at turn n represents the negative slope, $-y'$, of the previous turn, $n-1$.

In reality, a fractional tune close to the quarter integer resonance is usually not very practical.

Using more complex digital filters, a TFB can be realized with a single pickup placed at any location in the lattice. The correction kick would be calculated from data acquired from one location, but over a number of turns. The Hilbert transform, which provides two orthogonal vector components—commonly referred to in signal processing as the in-phase I and quadrature Q —is typically used, followed by a phase rotation. The scheme is often referred to as a Hilbert phase-shifter. A typical TFB architecture (for one pickup) using this principle with the Hilbert transform realized by a finite impulse response (FIR) filter is depicted in Fig. 3.12. The method is not limited to one pickup only. Any number of pickups can be processed in parallel and the resulting correction kick is obtained as a sum of individual pickup contributions. The Transverse Feedback System in the Large Hadron Collider is typically operated in this mode using 4 pickups per beam per plane.

Using the Hilbert transformer coefficients [71] and phase rotation terms, the FIR filter coefficients will be:

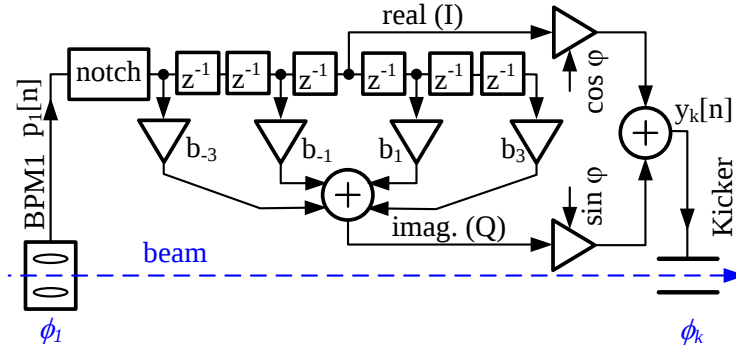


Figure 3.12: Typical signal processing for single pickup feedback using Hilbert phase shifter (7-taps). Sampling is once per turn per bunch passage, the structure is implemented for every individual bunch.

$$\begin{aligned}
 b_n &= \frac{2}{\pi n} \sin \varphi \quad \text{for } n \text{ odd} \\
 &= 0 \quad \text{for } n \text{ even} \\
 &= \cos \varphi \quad \text{for } n=0,
 \end{aligned} \tag{3.53}$$

where φ is the required phase rotation angle between pickup and kicker:

$$\varphi = \phi_k - \phi_1 + Q (\tau_{Hilbert} + \tau_{Notch} + \tau_{Other}) . \tag{3.54}$$

Q is tune, ϕ_1 and ϕ_k are the betatron phase advances at pick-up and kicker locations with respect to some fixed reference, $\tau_{Hilbert}$ is group delay (in turns) of the used Hilbert filter (in the example of Fig. 3.12, $\tau_{Hilbert} = 3$), τ_{Notch} is group delay (in turns) of the used notch filter (in this example $\tau_{Notch} = 0.5$) and τ_{Other} is other hardware or algorithm specific processing delay (in turns).

The frequency response of the Hilbert phase-shifter must be taken into account when using this method. Short filters exhibit a non-negligible ripple in the response that can be detrimental for certain values of fractional tune. Longer filters have a flatter response, but introduce more delay into the feedback loop. Operating close to integer, or half-integer tunes is practically impossible. As multiple samples from a number of consecutive turns are used for every correction kick calculation, pickup measurement noise is partly reduced.

The longer processing delay of the Hilbert phase-shifter method with respect to the Vector sum method limits the maximum feedback loop gain, the tune acceptance range is also narrower. Nevertheless, the Hilbert phase-shifter method is very popular in modern digital TFBs as it provides flexibility, it is easy to follow machine parameter evolution during the accelerating cycle (tune, optics change) and if multiple pickups are used it also provides an operational redundancy, as such a TFB can run with a single pickup only.

TFB signal processing in the Large Hadron Collider

A simplified block diagram of the digital signal processing of the LHC transverse feedback is shown in Fig. 3.13. The TFBs for each beam (1/2) and each plane (H/V) use four pickups located in the arcs around the former interaction point 4 (IP4), and their tetrode power amplifiers and deflectors are located in the LHC radio-frequency zone at IP4. Due to the TFB complexity, technical functionality is split into two modules. Beam position measurement is realized by a dedicated, very low noise beam position measurement module (BPM) providing a 1 Gbps datastream of one position sample per bunch per pickup passage (one data point every 25 ns) [72]. The BPM module interfaces to the RF signals from the pickups, adjusts the input gain to optimally measure bunches of all intensities used in LHC (from 1×10^9 to 4×10^{11} charges per bunch) and performs position normalization with respect to bunch intensity.

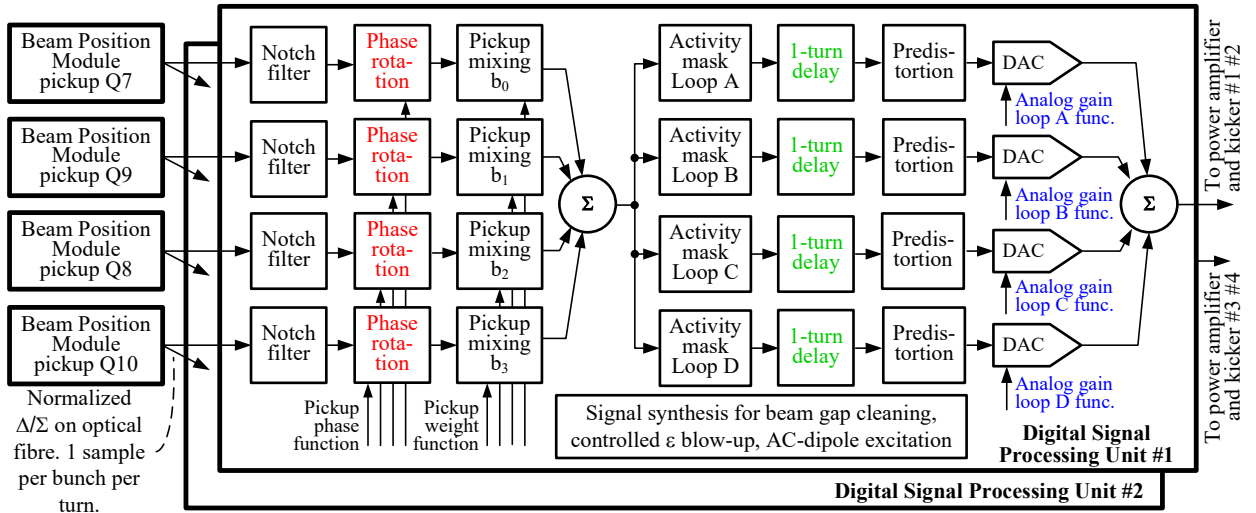


Figure 3.13: Simplified block diagram of the LHC transverse feedback signal processing. Two redundant signal processing units drive four sets of power amplifiers and kickers. Adjustment of parameters shown in color is critical for TFB performance.

Four digital streams of normalized beam positions are sent over fiber optic links to the digital signal processing module. In this module, the streams from all pickups are synchronized, and a notch filter is applied to suppress the closed orbit information. With a beam synchronous sampling clock, the notch filter also suppresses all other static signals, errors and imperfections seen by the beam position module and extracts only the oscillatory component relevant for TFB operation. Therefore, beam synchronous sampling and the notch filter relaxes already very demanding requirements for BPM electronics.

The LHC TFB has both previously mentioned signal processing schemes implemented: one Hilbert phase-shifter for each pickup controlled by a real-time function, Vector sum mode for pairs of pickups controlled by a real-time function, and an FIR filter with programmable coefficients for any other operational mode (e.g. the Kompola filters). The standard mode of LHC TFB

operation is phase-shifter mode for each pickup, as it is compatible with fast damping times (10-15 turns) and it can follow the dynamic LHC optics in real time (filter coefficients are recalculated and updated approximately every 12 turns). Four pickups per beam per plane provide quadruple redundancy.

The LHC TFB signal processing supports four independent feedback loops (“activity masks” in Fig. 3.13), where groups of bunches (within one turn) can be in real time assigned to loops with different dynamics, or other feedback features. Separate loops are used for example to treat the main LHC physics beam differently to the group of non-colliding, so called witness bunches which are needed for accelerator operation. Bunches can have strong damping of injection oscillations and then be handed over to a regular loop with lower gain.

The signal synthesis blocks generate signals for beam cleaning, white, or colored noise for controlled emittance blow-up, or AC-dipole like excitation for optics measurements. Signals can be injected into any of the four feedback channels. Each of the four outputs has individual pre-distortion filters to shape the signals and compensate the power system transfer function. Signals can be generated with a large bandwidth to, for example, manipulate single bunches within a 25 ns spaced bunch train, or provide an “ideal” bunch by bunch damper. Reduced bandwidth provides high strength kicks e.g. to use the TFB as AC-dipole excitation to probe dynamic aperture, or to generate a sustained 1 MW beam losses on primary collimators for the purpose of a magnet quench test.

3.2 TFB Parameter Identification

In the field of controls engineering, the relationship between the closed-loop transfer function and the open-loop transfer function is well established. This relationship can be expressed as a function of frequency ω :

$$CL(\omega) = \frac{OL(\omega)}{1 + OL(\omega)}. \quad (3.55)$$

In the context of a transverse feedback system, the open-loop transfer function is defined as:

$$OL(s) = GH_S(s) H_C(s) H_A(s). \quad (3.56)$$

Here, $OL(s)$ represents the combined transfer function of the beam, represented as G , along with the sensor, controller and actuator [73, 74].

For the system to maintain closed-loop stability, it is essential that the denominator of Equation (3.55) does not equal zero. This leads us to the stability criterion, which must be satisfied:

$$GH_S(s) H_C(s) H_A(s) < (-1). \quad (3.57)$$

To describe the overall feedback system more comprehensively, we can express it in the following form:

$$H_S(s) H_C(s) H_A(s) = K \cdot e^{j(sT + \phi_{PK})}. \quad (3.58)$$

By substituting Equation (3.58) into the stability criterion outlined in Equation (3.57), we derive the conditions necessary for stability:

$$|G| \cdot K < 1 \quad (3.59)$$

$$\arg\{G\} + \omega T + \phi_{PK} = -\pi \pm \text{tol}. \quad (3.60)$$

The key parameters that significantly influence the gain and phase margins, and consequently the overall stability of the feedback loop, include the loop gain K , the feedback phase ϕ_{PK} , and the total loop delay ωT . Knowing the actual values of these parameters throughout the machine cycle, and making precise adjustments are essential for optimizing the performance of the TFB. In the context of this thesis, these parameters will be systematically evaluated in the following as a part of the objectives #2 and #3.

3.3 Transverse phase space reconstruction

The following section aims in defining signal processing techniques and analysis algorithms which will allow to evaluate and quantify the parameters identified in Objective #2 and #3, from observables available within the transverse feedback system.

The LHC transverse feedback system provides bunch by bunch, turn by turn, normalized and digitized beam position signals from up to four pick-ups per plane and for each beam. Together with already existing powerful computer-based observation systems, this data can be used to reconstruct in real-time the transverse phase space coordinates of the centre-of-charges, for each individual bunch. Such information is extremely valuable for machine operation, or transverse instability diagnostics.

This section introduces methods of combining four position signals for such analysis in the presence of noise and with active transverse feedback.

One considerably useful representation of transverse motion is the use of phase space coordinates, readily described in Ref. [75] as an analytic signal $x[n]$, expressed as,

$$x[n] = y[n] + jy'[n]. \quad (3.61)$$

Here, the transverse normalized phase space coordinates $y[n]$ and $y'[n]$ represent normalized position data respectively the corresponding normalized slope values at turn index n .

For the analytic evaluation, we implicitly assume that the beam is centred in the pick-ups and we observe betatron oscillations, i.e. $(y)^2 + (y')^2 = \text{const.}$ Furthermore, for our assessment, we shall use a damped, complex-valued harmonic oscillator as beam model, which provides for the k^{th} beam position monitor at the n^{th} turn the phase space coordinates as follows,

$$x_k[n] = A_0 e^{-j\phi_k} (\alpha \cdot e^{-j\omega_0})^n. \quad (3.62)$$

Here, A_0 and ϕ_k are initial conditions, α accounts for an amplitude decay and $\omega_0 = 2\pi Q_f$ represents the angular frequency at the fractional betatron tune Q_f .

In order to satisfy Eq. (3.61), and by acknowledging that the ADT Beam Position Monitors readily provide normalized readings, we are looking for indirect methods to obtain slope samples from beam position measurements.

In the following, we evaluate two methods for combining beam position data of four LHC pick-ups, identified as a *spatial* and a *temporal phase shift* in Section 3.3, Ref. [76]. The first combines the information of several beam position monitors based on their longitudinal distribution in the accelerator, the later relies on processing the history of recorded beam position data using filter kernels.

3.3.1 Spatial method

This method relates the data measured by two or more independent beam position monitors at different longitudinal azimuths. Fig. 3.14 outlines the case for $N = 2$ signal sources. For this method, the beam position monitors should have a betatron phase advance ideally between $60^\circ < (\phi_2 - \phi_1) < 120^\circ$.

For the case of the LHC ADT, the data provided by individual beam position monitors $y_k[n]$ are meticulously time-aligned during setting-up, with index n corresponding to the same bunch data at the same turn. Therefore, using the ‘‘Pick-up Vector Sum’’ algorithm from Equation (3.50) it can be shown that, choosing appropriate mixing coefficients a_{11} and a_{12} , the position signal $y_I[n]$ in Fig. 3.14 of a virtual beam position monitor can be constructed, such that

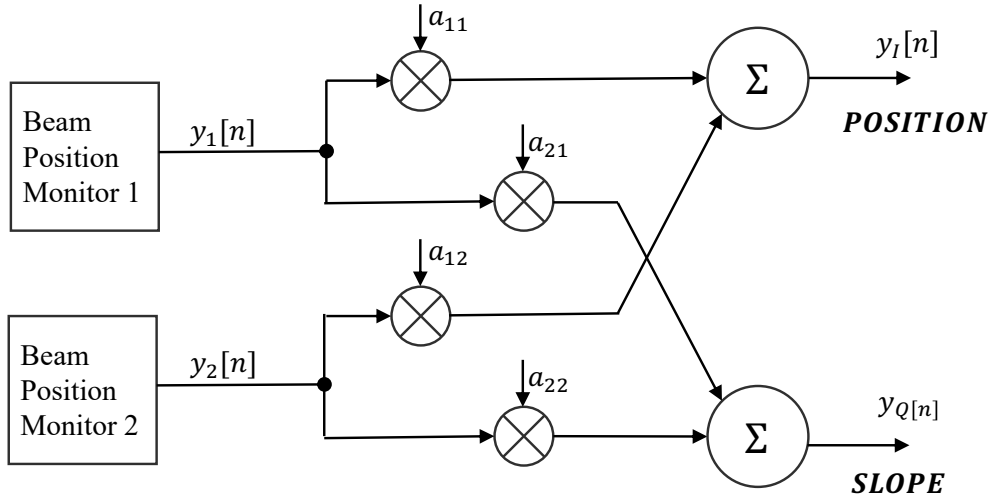


Figure 3.14: Spatial phase space reconstruction: in-phase term $y_I[n]$ and quadrature component $y_Q[n]$ calculated from vectorial rotation and combination of two beam position sequences $x_1[n]$ and $x_2[n]$.

$$y_I[n] = a_{11}y_1[n] + a_{12}y_2[n]. \quad (3.63)$$

Equivalently, applying the same approach of pick-up signal mixing, and by taking into account an additional 90° phase advance compared to the virtual beam position used for Eq. (3.63), we obtain the representation of the slope, $y_Q[n]$, described as

$$y_Q[n] = a_{21}y_1[n] + a_{22}y_2[n]. \quad (3.64)$$

The pair of Eq. (3.63) and (3.64) represent Cartesian coordinates, describing the reconstructed phase space for an arbitrary longitudinal position. It is a convenient practice to chose the ADT kicker position as reference for the phase space reconstruction. By using the same longitudinal reference this technique is further expandable for using multiple beam position monitors – four in the case of the LHC ADT – as shown in Fig. 3.15.

We therefore obtain an analytic signal $x_S[n] = y_I[n] + jy_Q[n]$ as the reconstructed normalized transverse phase space based on a scalar combination of real-valued position sequences, $y_k[n]$, using

$$x_S[n] = h_0[n] * \sum_k (a_{1k} + ja_{2k}) \cdot y_k[n]. \quad (3.65)$$

The asterisk operator (*) represents the discrete-time convolution of the weighted BPM signals with an additional finite impulse response (FIR) filter of impulse response $h_0[n]$, allowing shaping of the input noise. When no filter is used, this method has zero group delay and therefore it is suitable for applications requiring low latency.

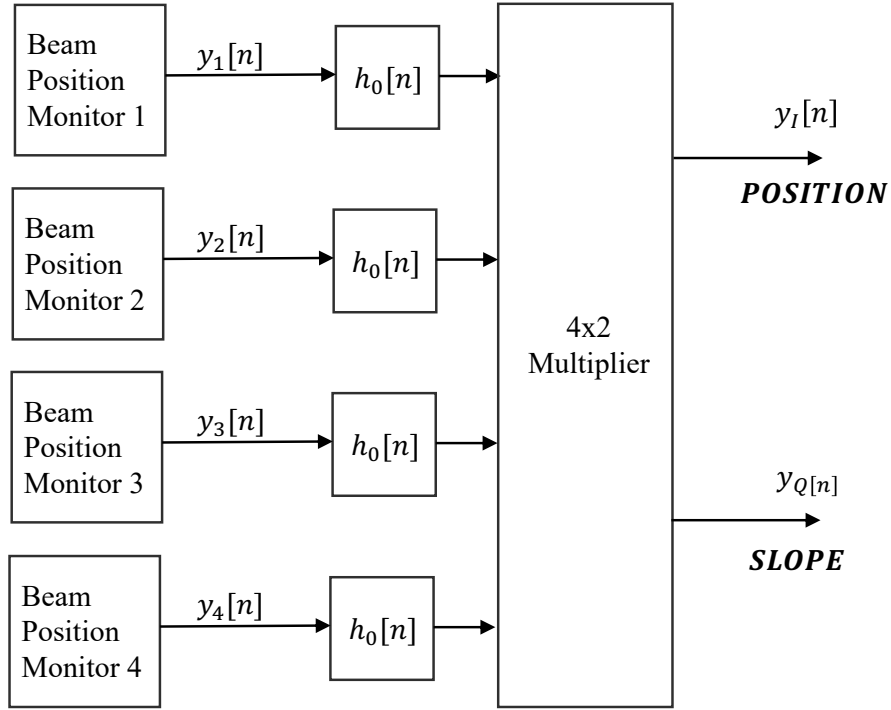


Figure 3.15: Spatial combination of four beam position streams.

3.3.2 Temporal method

Referring to Equation (3.52) [75], this reconstruction method obtains the slope signal as the 90° phase rotated version of the position data utilizing digital filters.

In order to reconstruct the analytic signal in Eq. (3.61) we are looking for a solution that allows to transform a sequence of position samples, $y[n]$, into a sequence of corresponding slope samples, i.e.

$$y'[n] = L\{y[n]\}. \quad (3.66)$$

Thereby, the operation denoted by $L\{\cdot\}$ in Eq. (3.66) is commonly known as *Hilbert transform* and is explained for example in Ref. [68].

A more practical approach can be found by noticing that $y'[n]$ is the 90° phase-rotated version of $y[n]$. This phase shift can be generated by simple means of digital filtering — as it is already been done in the feedback phase controller [76].

Figure 3.16 shows how the phase space is reconstructed by means of two individual digital filters. The two branches with filter kernels $h_I[n]$ for the in-phase component, and $h_Q[n]$ for the quadrature component generate two quadrature output signals, named $y_I[n]$ and $y_Q[n]$, which can be combined to a final analytic signal, representing a reconstruction of the transverse phase space,

$$c[n] = y_I[n] + jy_Q[n] = y[n] * (h_I + jh_Q). \quad (3.67)$$

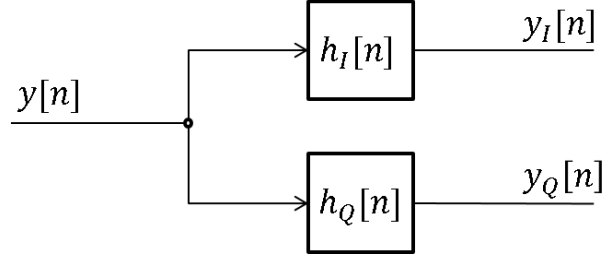


Figure 3.16: Phase space reconstruction using two digital filters.

As an intermittent research result, elaborate filter kernels including DC suppression were defined, tuned for the fractional tunes of the particular plane, to attenuate out-of-band signals. Examples of filter kernels for fractional tunes used in the LHC transverse feedback systems are listed in Table 3.1. With only five coefficients these filters are usable with possible damping times of 10 turns or less.

Table 3.1: Filter kernels LHC.

(a) Horizontal, $Q_f = 0.275$		(b) Vertical, $Q_f = 0.31$	
$h_I[n]$	$h_Q[n]$	$h_I[n]$	$h_Q[n]$
-0.1837	+0.0447	-0.1322	+0.1136
-0.1224	-0.4922	-0.1983	-0.4542
+0.6122	+0.0000	+0.6612	+0.0000
-0.1224	+0.4922	-0.1983	+0.4542
-0.1837	-0.0447	-0.1322	-0.1136

As outlined in Fig. 3.17, bunch-by-bunch data $y_k[n]$ provided from individual Beam Position Monitors passes through a pair of matched filter kernels, denoted as $h_I[n]$ as $h_Q[n]$. The filters' even and odd symmetric impulse responses generate in-phase (I) and quadrature output signals (Q), which can be combined afterwards thanks to an identical group delay.

It is worth noting that the calculated FIR filter output pairs readily represent phase space coordinates at the longitudinal position of the corresponding monitor. Therefore, to aggregate four pick-ups to an arbitrary longitudinal reference location, the individual output vectors need to be aligned before summing their contributions. This is done by a vector rotation, ϕ_k , towards a common longitudinal position (e.g. to the location of the ADT kicker).

The analytic signal $x_T[n] = y_I[n] + jy_Q[n]$ obtained from the temporal method can therefore be described as,

$$x_T[n] = \sum_k (y_k[n] * (h_I[n] + jh_Q[n]) e^{j\phi_k}). \quad (3.68)$$

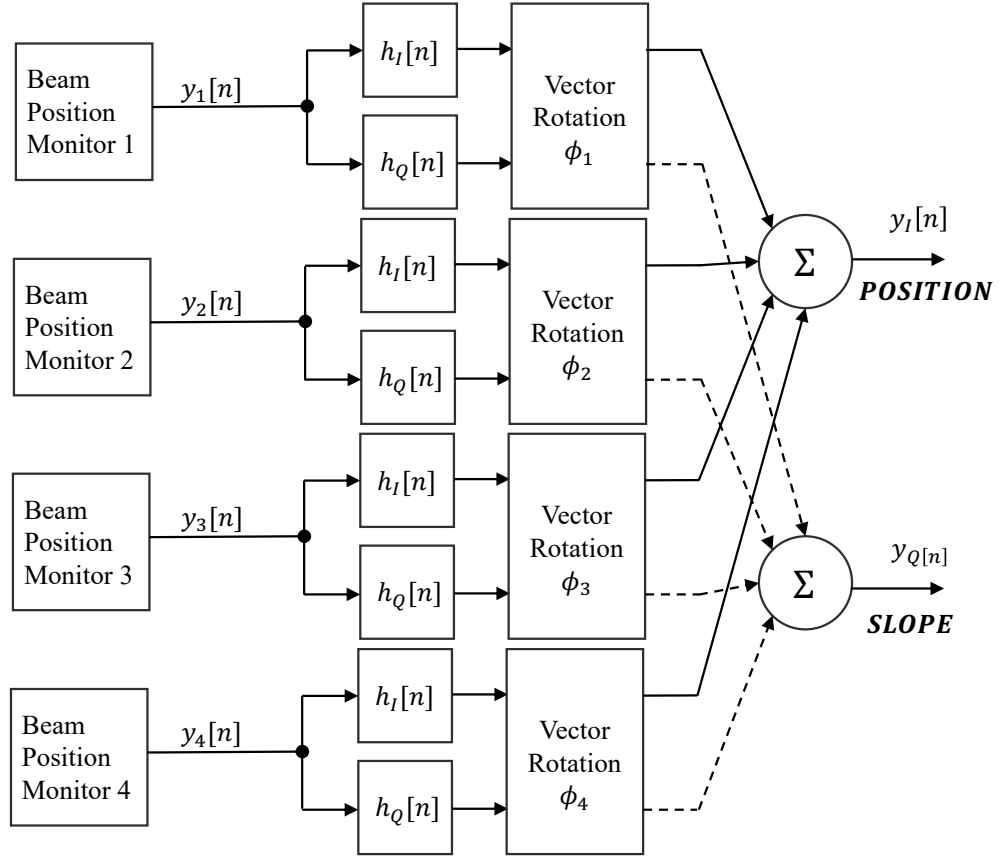


Figure 3.17: Temporal phase space reconstruction using matched digital filters $h_I[n]$ and $h_Q[n]$ on the input data stream $y_k[n]$ of four Beam Position Monitors.

With a short 5 taps kernel length, these filters are tuned to exhibit nominal transmission at the fractional tune for the corresponding plane, rendering them applicable for a tune range exceeding ± 0.02 around the target tune [75].

The suggested methods in Section 3.3 are both valid candidates for reconstructing the transverse phase space in real-time. With the spatial method being attractive for the analysis of fast beam transients, for example during injection transients and with 5 turns damping time, both methods profit from the suppression of out-of-band noise using filter kernels which improves the SNR.

Potentially, more elaborate filter response functions can be designed to lower the SNR even further, for instance by processing the beam position data of 100 to 1000 turns.

3.4 TFB parameter extraction

We describe a method for feedback parameter extraction, as required by Objective #1. This

method is based on transverse excitations generated by the kicker of a TFB. It involves reconstructing the transverse phase space using digital filters for each individual pick-up, as detailed in Section 3.3. The analysis is conducted entirely in the time domain, without any conversion to the frequency domain.

For our analysis we recall 3.61, an analytic signal $x[n]$ which describes the evolution of a particle in normalized transverse phase space coordinates

$$x[n] = A_0 e^{-j\phi_0} (\alpha \cdot e^{-j\omega_0})^n. \quad (3.69)$$

For simplicity we assumed that the particle motion is dominated by active damping (see also Ref. [77]), thus reducing the analysis to linear optic effects of the magnetic guidance field and exponential amplitude decay. Equation (3.69) describes a damped harmonic oscillation at turn index n , with angular frequency ω_0 and a decay factor, α , and with initial amplitude and phase denoted as A_0 resp. ϕ_0 . Note that the negative exponents preserve the direction of rotation in normalized phase coordinates (positive phase $\mapsto$ clockwise; downstream).

In order to extract essential parameters of a transverse feedback system from bunch-by-bunch beam data we shall consider the case of a beam in a steady state — any transients have settled — which has been excited transversely by the TFB for less than one turn (illustrated in Fig. 3.18).

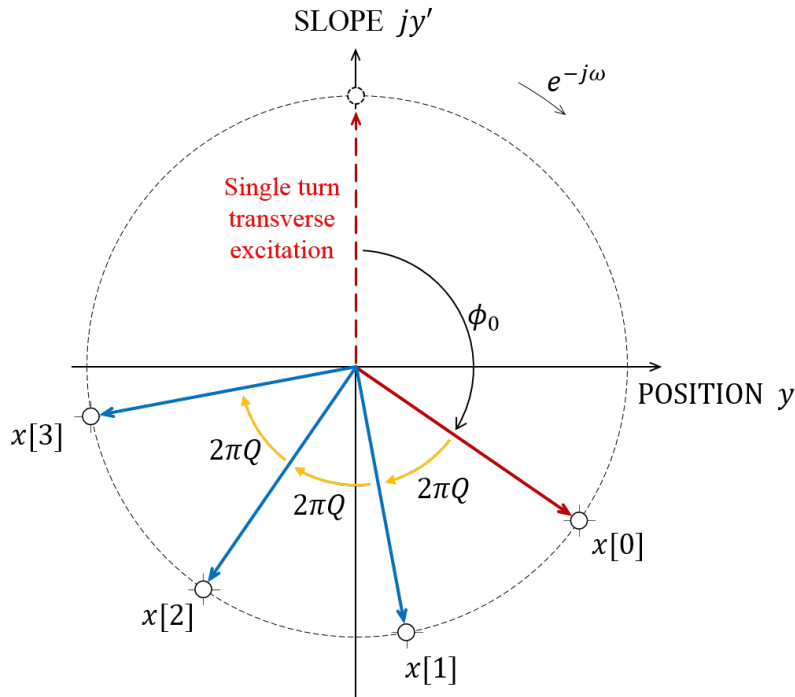


Figure 3.18: Transverse phase space plot (normalized) at the position of a pick-up. A transverse deflection commutes from the location of the kicker to the coordinates of the pick-up by a fixed phase angle (denoted as ϕ_0), with subsequent turns advancing in phase by the fractional tune ($\Delta\varphi = 2\pi Q$).

3.4.1 TFB gain

We define the transverse activity, $A[n]$, as the magnitude of the vector $x[n]$,

$$A[n] = \text{abs}\{x[n]\} , \quad (3.70)$$

which is a measure of the instantaneous oscillation amplitude in the normalized transverse phase space.

From Eq. (3.69) it follows that,

$$A[n] = A_0 \alpha^n , \quad (3.71)$$

with the magnitude A_0 defined by the initial excitation amplitude of the transverse deflection at turn $n = 0$. If $A[n]$ decreases over time then the transverse activity is considered to be damped, whereas growing values provide an indication of transverse instability.

By noting that the change in amplitude per turn in Eq. (3.71) is constant and defined by the decay factor $\alpha \equiv e^{-1/\tau_d}$, we can derive the decay time τ_d from the transverse activity. This is done by comparing two time instances, n_1 and n_2 , using the following equation:

$$\tau_d = (n_2 - n_1) \left(\log \frac{A[n_1]}{A[n_2]} \right)^{-1} . \quad (3.72)$$

In control systems, the damping time τ_d is inversely related to the product of the damping ratio ζ and the natural frequency ω_n , expressed as $\tau_d = \frac{1}{\zeta \omega_n}$. This relationship is fundamental in understanding how feedback influences system dynamics, particularly in terms of response speed and stability [78]. For weak internal damping, this relationship can be further simplified to $\tau_d = \frac{2}{K}$, where K is the feedback gain.

Rearranging this equation allows us to express the feedback gain as a function of damping time:

$$K = \frac{2}{\tau_d} . \quad (3.73)$$

For a detailed analysis of the effect of damping feedback on a second-order system, we refer to Appendix ??, where we derive the relationship discussed.

3.4.2 TFB phase

As shown in Fig. 3.18, in the very same turn when the kick ($\pi/2$ or $+j$) has been applied, i.e. $n = 0$, the betatron phase advance between kicker and pick-up effectively transforms the transverse deflection in normalized coordinates, thus leading for the initial condition of Eq. (3.69),

$$\phi_0 = \frac{\pi}{2} - \arg\{x[0]\} . \quad (3.74)$$

More generally, according to Eq. (3.82) we notice that any subsequent beam oscillations recorded by the pick-up will advance by the fractional tune. We can therefore determine also for later turns an initial phase, $\psi[n]$, from the argument of the analytic signal by including a linear phase term,

$$\psi[n] \doteq \frac{\pi}{2} - \arg\{x[n] \cdot e^{j2\pi Q \cdot n}\} . \quad (3.75)$$

From this we instantly obtain the phase advance between the kicker and the pick-up by averaging over M consecutive turns,

$$\zeta = \frac{1}{M} \sum_{k=0}^{M-1} \psi[k] . \quad (3.76)$$

3.4.3 TFB delay

For the stability of a TFB it is essential that kick signals are well aligned with the time of arrival of the bunches. In the following we derive a method which aims on quantifying the kicker delay offset.

We now consider the case of a kick signal which is modulated in amplitude over one turn. Thereby, a sinusoidal kick waveform with M periods per machine turn is sampled by a bunch with index k depending on the time of arrival at the location of the kicker. The resulting bunch oscillation magnitude, described as,

$$A_k = A_0 \cdot \cos\left(\frac{2\pi M}{h} \cdot k + 2\pi M \cdot \eta\right) , \quad (3.77)$$

is then recorded as betatron oscillation decay at a downstream pick-up. Here, the harmonic number h represents the maximum number of buckets per turn, and a delay offset factor, $\eta = \Delta T / T_{\text{Rev}}$, defined as the ratio between the kicker delay offset, ΔT , and the revolution period, T_{Rev} .

If this kick exercise is repeated with two phase-shifted versions of the modulation signal in quadrature, denoted as A_I and A_Q , we can reconstruct an IQ-footprint of the traversing bunches at the kicker as,

$$\chi[k, n] = A_I[k, n] + jA_Q[k, n] . \quad (3.78)$$

As can be easily verified, bunches are equally distributed around a circle with constant radius. Therefore, unwinding the phase response of Eq. (3.78) by taking into account a linear position-dependent phase term,

$$\rho[n] = \arg\{\chi[k, n] \cdot e^{-2\pi M k / h}\} , \quad (3.79)$$

and averaging over populated bunches and N turns results in,

$$\theta = \frac{1}{N} \sum_{m=0}^{N-1} \rho[m] \doteq 2\pi M \cdot \eta . \quad (3.80)$$

Since $\eta = \Delta T / T_{\text{Rev}}$ it follows for the delay offset:

$$\Delta T = \frac{\theta}{2\pi M} \cdot T_{\text{Rev}} . \quad (3.81)$$

It is worth noting that the offset factor in Eq. (3.77) is weighted by M , thus increasing the sensitivity to delay offsets. Ultimately, if $M = h$ then the resulting phase in Eq. (3.79) depends solely on the delay offset factor.

3.5 Accelerator parameter extraction

Objective #3 calls for investigation and proposal of methods and required signal processing techniques to extract vital accelerator parameters from observables available within the transverse feedback system. The parameters of interest would be bunch-by-bunch machine tune and damping time. The data or results should be preferably available in real time or immediately after injection.

3.5.1 Bunch-by-bunch tune

The single-turn excitation transients described in Section 3.4 provides us sufficiently large oscillation amplitudes for a duration of several of turns (typically 5 - 100, depending on the requested feedback gain), to extract the turn-by-tune.

By rewriting Eq. (3.69) as recurrence formula we obtain the coordinates for consecutive turns by evaluating

$$x[n] = x[n - 1] \cdot \alpha e^{-j\omega_0} . \quad (3.82)$$

As can be seen, after a turn the sequence has advanced in phase by $\Delta\varphi = \omega_0 \equiv 2\pi Q$. Therefore, by taking the ratio over two consecutive turns we can express the per-turn or instantaneous fractional tune, $Q[n]$, as

$$Q[n] = \frac{1}{2\pi} \arg \left\{ \frac{x[n - 1]}{x[n]} \right\} . \quad (3.83)$$

It is worth noting that Eq. (3.83) allows for correctly characterizing the fractional tune to be below or above the half-integer resonance.

3.5.2 Damping time

Equation 3.72 already describes the bunch-by-bunch damping time, which can be extracted from transverse activity data.

Chapter 4

Results

In this chapter, we present the results of our research, which aims to verify and validate the methods outlined in Chapter 3.

To address Objective #1, we implement a brief transverse excitation of a bunch using the TFB kicker, which results in controlled beam oscillations and we employ numerical simulations and particle tracking code to assess whether this method is detrimental to the beam.

The Measurements section focuses on analysing results obtained from real beam data collected during the LHC 2024 commissioning. The data, recorded with the assistance of the TFB observation systems, is utilized for a comprehensive verification of the described methods. This is followed by detailed measurements aimed at evaluating the sensitivity of each method to variations in parameters. Objective #2 involves the evaluation of TFB parameters, while Objective #3 pertains to accelerator parameters. Both objectives are thoroughly analysed in the context of the LHC TFB, with results presented from data collected during the regular machine start-up.

The subsequent section addresses Objective #4, demonstrating the practical application of the proposed methods. We detail the real-time extraction of transverse activity for each individual bunch, a metric introduced by this study that has become increasingly significant for machine operation.

Finally, the concluding section of this chapter is dedicated to advanced signal processing techniques and digital filter design. Here, we present our findings related to Objective #5, which focuses on enhancing the robustness of transverse feedback systems in the context of tune variations.

4.1 Measurements

In this section, measurements obtained from real beam data during the LHC 2024 run will be utilized to verify and confirm the described methods in Sections 3.3, 3.4 and 3.5, as well as to identify areas for improvement. By comparing the actual data with the expected results, any discrepancies will be highlighted.

4.1.1 Method verification

During the regular machine start-up following the year-end technical stop (YETS 2023/24), the LHC was carefully prepared with circulating beams as part of the transverse feedback commissioning process. This preparation aimed to ensure the proper functioning of all TFB components and to optimize performance for the upcoming run.

As part of this effort, measurements were taken with both beams filled with 12 witness bunches and two batches of 72 bunches. Witness bunches are strategically placed in specific bucket locations with intentionally reduced TFB gain. This setup is crucial because it allows the LHC tune measurement system (BBQ) to reliably detect the machine's tune, even in the presence of a strong transverse feedback system and its highly sensitive beam position monitors.

The two sets of 72 nominal bunch trains were each configured with standard TFB gain to achieve nominal damping times. Importantly, all TFB settings were carried over from the previous 2023 run, facilitating a seamless transition into the 2024 operational phase. The settings were not guaranteed to be the most optimal nevertheless. By default, the TFB was active during injection and the flat bottom plateau to preserve the beam's transverse emittance.

Phase space reconstruction method

For the analysis, experimental data was collected in April 2024 from the eight ADT processing modules, with two systems per plane and per beam. The dataset includes information from four pick-ups. Figure 4.1 displays the data acquired by the ADT observation system, where each color represents raw data from a single pick-up, labeled Q7 to Q10, corresponding to the quadrupole magnets where they are installed.

The data points indicate the normalized transverse position information recorded by the associated beam position monitor (see Section 3.1.2). At the system's sampling rate of 40 MSPS (or 25 ns per sample point), the equivalent record length of the x-axis is approximately 13.1 ms. The y-axis is represented in 16-bit encoded signed binary codes, allowing for a value range of $[-32\,768, 32\,767]$, corresponding to a transverse beam movement in the TFB pickups of ± 1.5 mm ($\pm 1.7\sigma$ at injection energy and $\pm 6.8\sigma$ at flat top).

Notably, based on the data in Figure 4.1, the mean beam position of pick-up Q7 (blue trace) is not well centered, unlike the other three pick-ups. A well-centered beam in the pick-up is crucial

to avoid potential saturation issues with the ADCs during large transverse beam excursions, which may occur for example during the setting-up phase of the injection system.

Upon carefully inspecting the raw traces, one can observe a low-amplitude oscillation, or ‘wiggle’, present during the first 60 turns. This is active short, controlled excitation at the beginning of the record, generated by the ADT controller and applied to the beam using the ADT kicker.

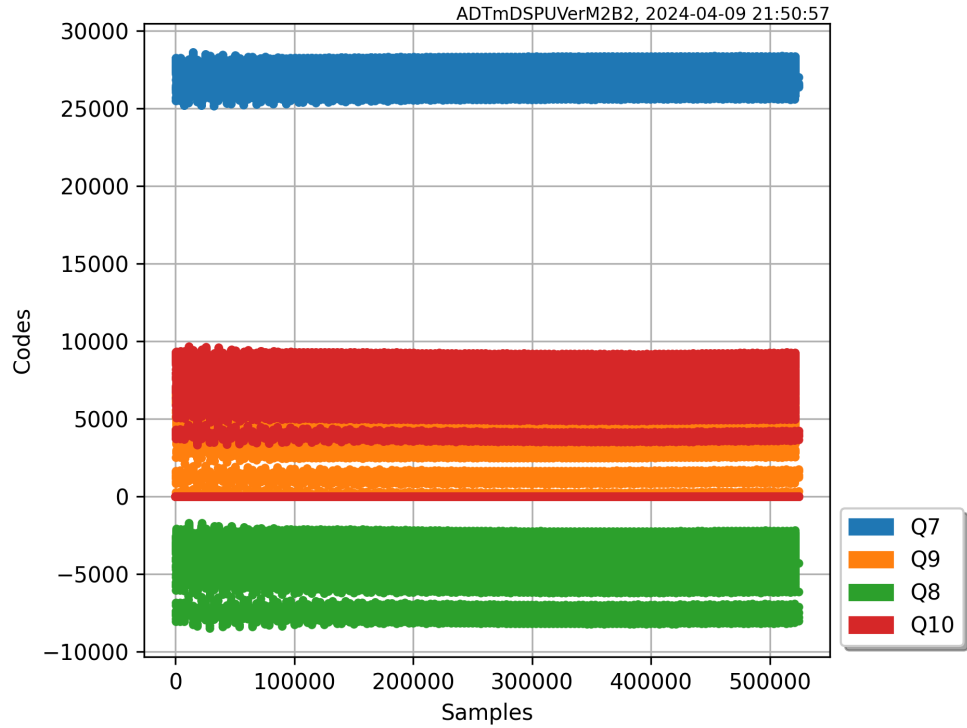


Figure 4.1: Raw data from four pick-ups captured by the ADT observation system, totaling 524 288 samples per data stream.

A detailed snapshot of this excitation is shown in Figure 4.2. The green trace represents the transverse positions recorded during the first three turns. At turn number 2, the ADT triggers a precisely timed single turn excitation (orange trace), which lasts exactly one turn, or 3564 samples. As shown, the excitation amplitude drops to zero before the position data of turn 3 is recorded.

Time synchronization with the circulating beam is important, to ensure that the response is truly representing an impulse response function. Additionally, periodic waveforms are intentionally selected, like the cosine excitation pattern shown with $N = 1$ (number of oscillation periods per turn), to ensure that the mean excitation voltage is zero. The applied excitation waveform discharges the kicker to zero voltage within the same turn when applied, thus the AC coupling of the ADT power system does not pose a problem.

In this demonstration, we observe that for the selected cosine excitation with $N = 1$, the deflection voltage for the circulating bunches in the machine remains nearly at full scale.

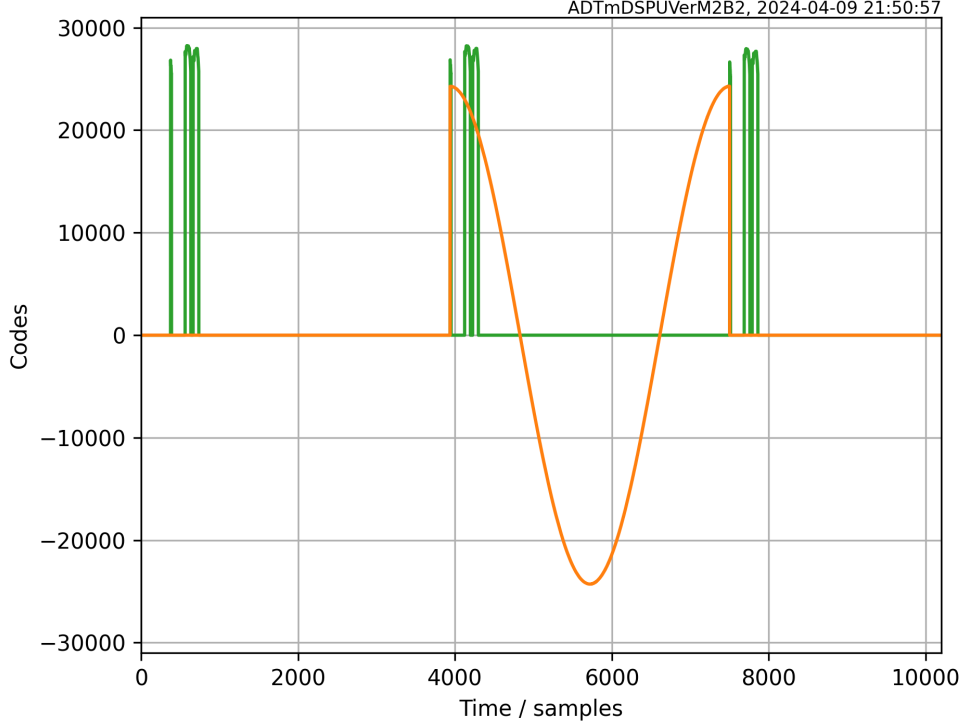


Figure 4.2: First 3 turns of pick-up data with cosine excitation pattern ($N=1$) applied during the second turn.

Since unpopulated bunches with zero intensity do not provide position readings, the recorded data retrieved from the ADT observation system primarily consists of zero values. Out of 3564 buckets, there are $12 + 2 \times 72 = 156$ populated bunches. This means that less than 5% of the recorded 524 288 samples contains actual information.

To better visualize and process the data, we first reorganize the vector of continuous readings into a two-dimensional format with dimensions turns $\times$ buckets. In our example, this would result in a matrix of size 147×3564 , with some unused samples at the end. However, in the current implementation of the ADT observation system, the record does not start with bucket 0, which means we need to drop some samples also at the beginning. As a result, the matrix shape becomes 146×3564 .

Next, we focus only on the buckets that contain bunches with an intensity above a preset threshold value. This refinement alters the matrix dimensions to turns $\times$ bunches, which, for the purpose of this demonstration, evaluates to 146×156 per pick-up. With this setup, we can visualize the time evolution of each individual bunch on a turn-by-turn basis, as illustrated in Figure 4.3 for the data from one pick-up and 156 bunches. As shown, the applied one-turn

excitation causes all bunches to oscillate coherently lower than 0.05σ , while the TFB action subsequently dampens this oscillation over approximately 20 to 60 turns.

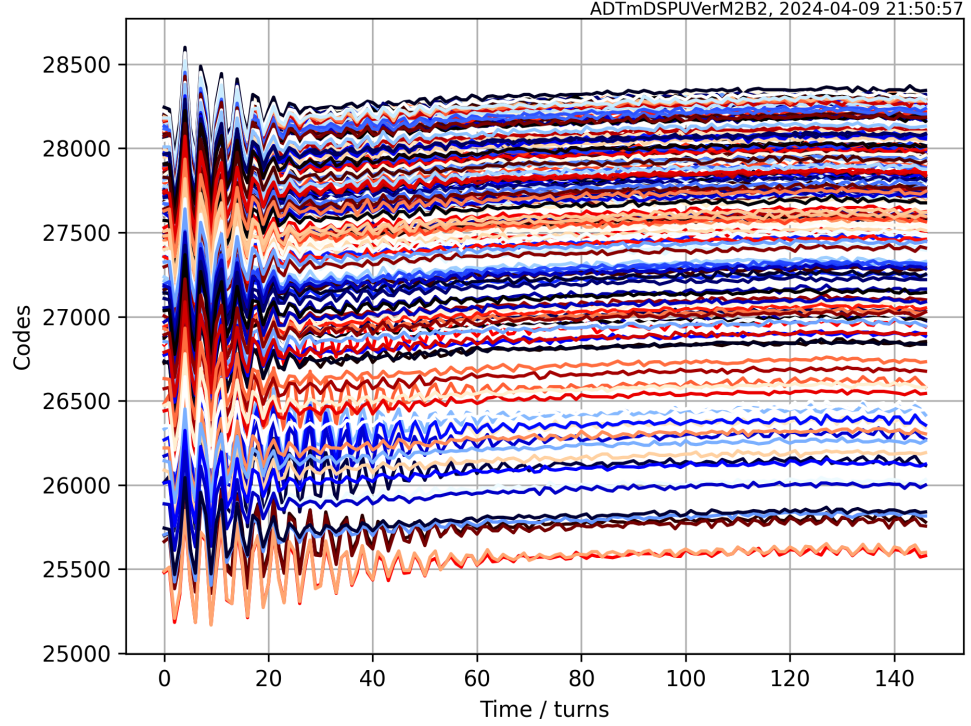


Figure 4.3: Analyzing single pick-up data: Bunch-by-bunch turn-by-turn position over 146 turns. Baseline offset is due to the beam not centered in this pickup and slightly drifting. The excitation amplitude is very low, 1000 codes on vertical axis corresponds to 0.05σ movement.

Each of these bunch-by-bunch traces is now analyzed according to Eq. (3.67), and the results are utilized to reconstruct the transverse phase space plots. Figure ?? presents the application of the two reconstruction filter kernels detailed in Section 3.3, Table 3.1. Notably, in comparison to Figure 4.3, both traces demonstrate a zero mean position. This outcome is a direct result of the notch filter implemented in the FIR filter kernels, which effectively mitigates unwanted frequency components.

The filtered one-dimensional turn-by-turn input data is now prepared for visualization as a two-dimensional transverse phase space plot, as shown in Figure 4.5. As anticipated, the feedback action plays a crucial role in the dynamics of the system, resulting in the reconstructed traces exhibiting a pronounced spiraling behaviour toward the center over consecutive turns. This spiraling effect indicates the system's stabilization process, where the feedback effectively reduces deviations from the desired trajectory (closed orbit). We are particularly interested in analyzing these traces, as they contain valuable information about the feedback system, its performance, and specific parameters that influence the accelerator operation.

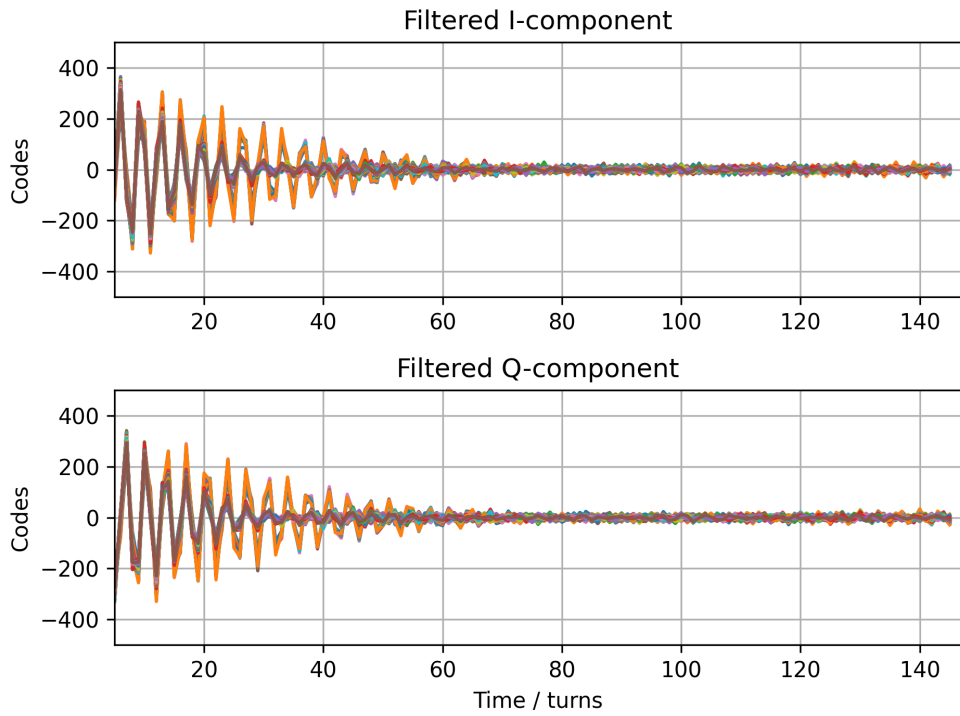


Figure 4.4: Filtered I and Q components plotted after the decay of filter transients.

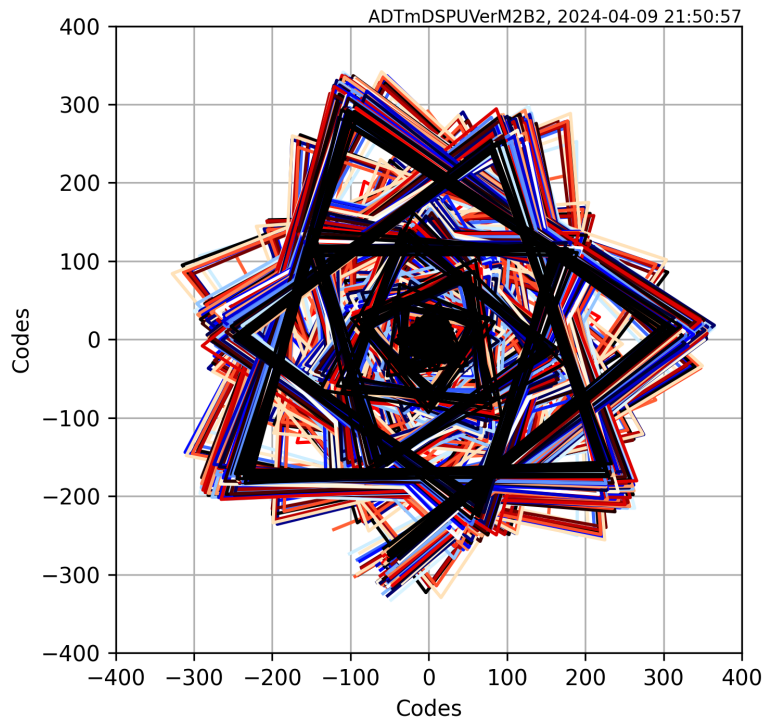


Figure 4.5: Transverse phase space plot reconstructed using single pick-up data and I/Q filtering.

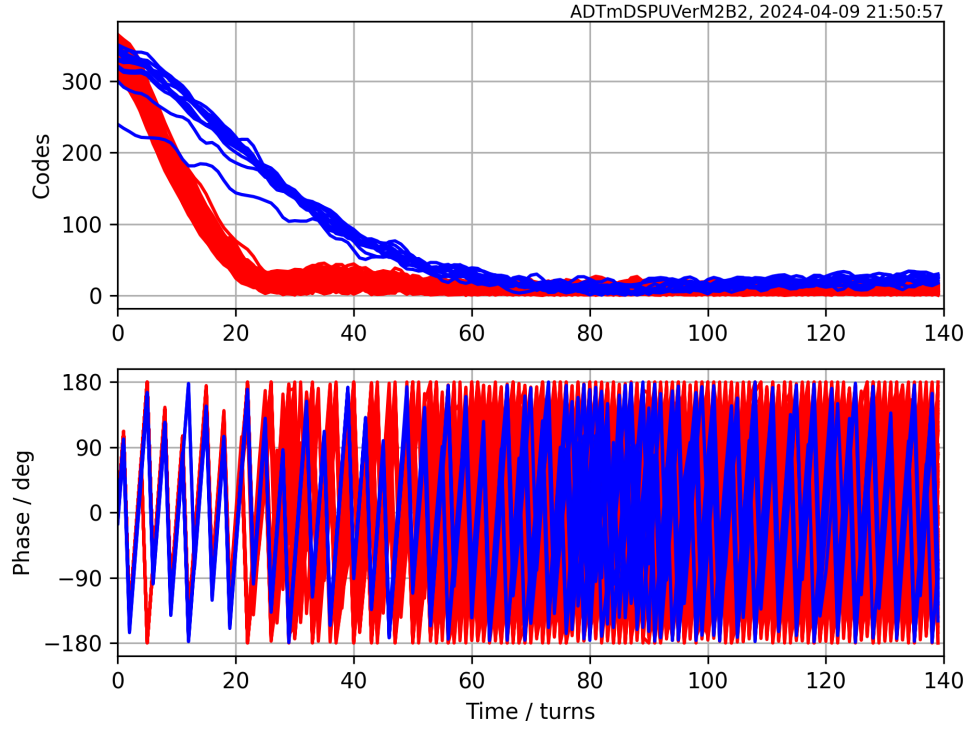


Figure 4.6: Transverse phase space analysis: amplitude (top) and corresponding phase plots (bottom).

Transverse Activity and Damping Time

By using the reconstructed phase space as input data, Equation (3.70) quantifies the transverse activity in terms of instantaneous oscillation amplitude, or envelope (represented by the blue and orange traces).

The left plot of Figure 4.7 evaluates the transverse activity over time for Witness bunches (blue traces) and Main bunches (red traces). A visual inspection of this figure reveals two clearly separated clusters, indicating different damping regimes. This behaviour is expected, as we have Witness bunches experiencing a lower TFB gain compared to Main bunches. While the red traces overlap well, the blue traces exhibit some scatter. This variation results from the initial oscillation amplitude, as can be seen in the right-hand plot of Figure 4.7. Despite the cosine excitation function with $M = 1$ being requested to start at bunch position 0, the effective kick voltage seen by the beam cannot respond instantaneously due to power and bandwidth limitations in the actuator component. Consequently, the first 12 bunches display the charging behaviour of the kicker and amplifier system, with bunch 0 receiving the lowest deflection kick.

To mitigate this issue, one could adjust the synchronization window of the excitation pattern to start before bucket 0, allowing sufficient time for the kicker to charge up to the nominal voltage. However, this adjustment must not affect the mean voltage sent to the power system, and each bunch must be kicked only once.

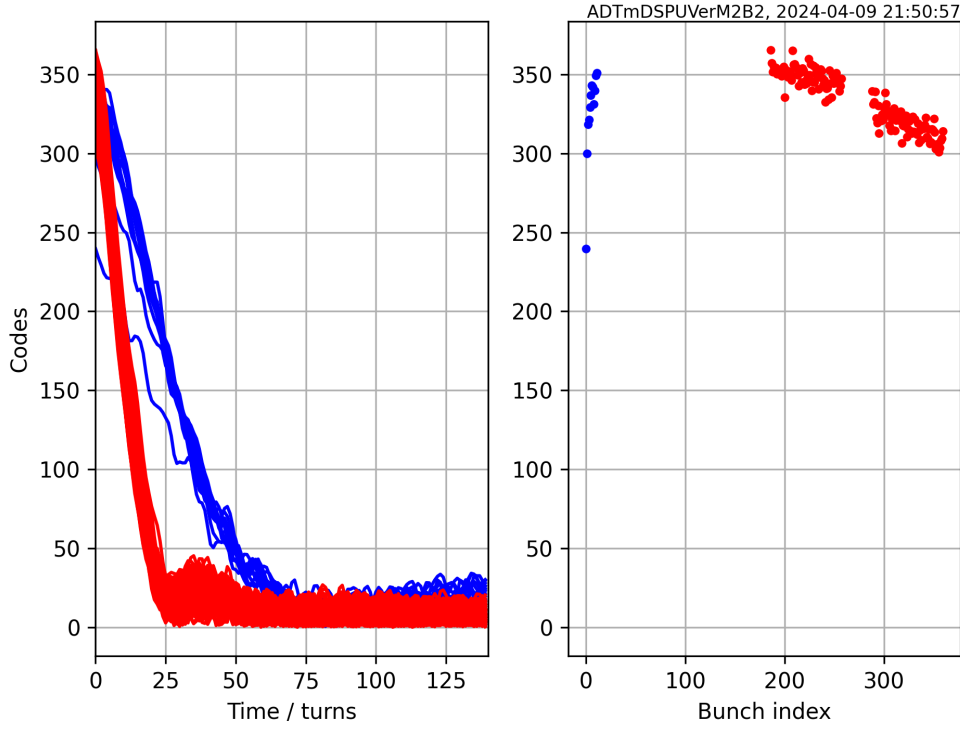


Figure 4.7: Comparison of oscillation amplitude decay over time (left plot) and peak oscillation amplitudes per bunch at turn 6 (right plot) for bunches 1 to 12 (blue traces) and two trains of 72 bunches (red traces). Movement of 400 codes corresponds to 0.02σ .

Using the previously derived transverse activity per bunch, Equation (3.72) defines the decay factor, also known as the damping time. Figure 4.8 displays two black dashed curves overlaid on the left plot, representing the estimated damping times for bunches 10 and 200, based on an exponential decay model. The decay time constant for all bunches can be obtained from the right graph.

The estimation model clearly distinguishes between the two damping regimes, with damping times for the Witness region estimated to be between 25 and 30 turns, while the Main bunches are damped at approximately 10 turns.

Referring to the first-order difference equation (3.18) in Section 3.1.1, we have:

$$x[n] = \alpha x[n - 1] \quad n > 0.$$

This recursion formula defines the observed beam position at turn n in relation to the position at the preceding turn. From this equation, one can readily deduce that for any non-zero value of α , the sequence will either grow or decay exponentially¹. This behaviour aligns with our expectations for a pure P-controller, where the corrective action is proportional to the error input.

¹An exception occurs when $\alpha = 1$, which results in a steady oscillation that preserves the amplitude.

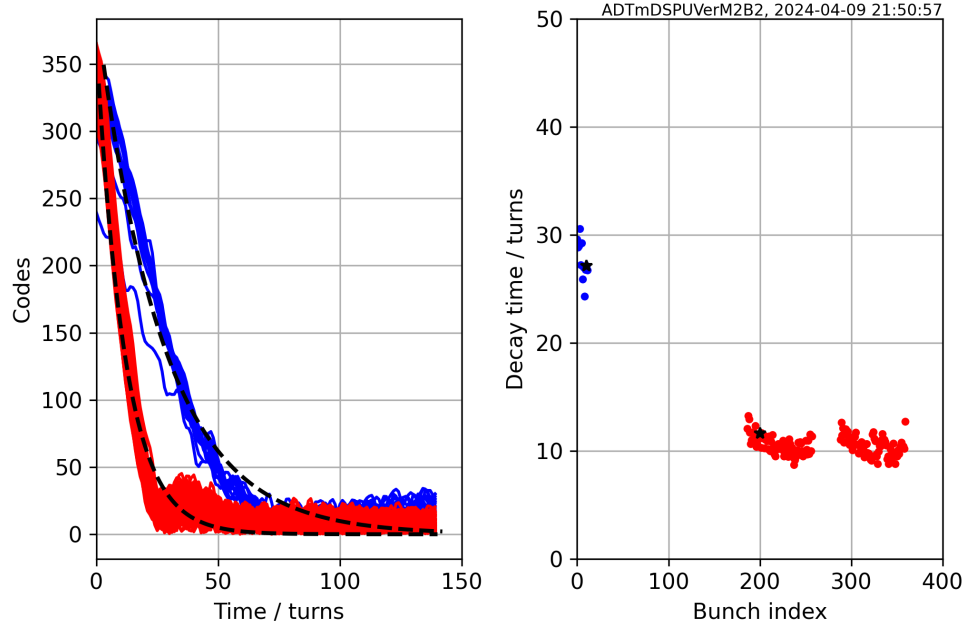


Figure 4.8: Oscillation amplitude decay over time (left plot) and exponential decay time estimation per bunch (right plot). The black dashed lines represent exponential decay curves for bunches 10 and 200, with time constants and peak amplitudes derived from the estimates.

Regular monitoring of system performance is essential to proactively identify feedback issues. This capability is now achievable, thanks to the signal processing method introduced in this thesis.

Tune Estimation

In this section, we continue to utilize the reconstructed phase space as input data, as was done in the previous section, and shift our focus to the evaluation of the argument of the phase space. Figure 4.6 provides a comparative analysis: the upper graph depicts the previously described transverse activity, while the lower graph presents the corresponding phase.

The comparison of the two graphs underlines that, in the presence of noise, the extracted phase data deteriorates as the initial oscillation amplitude decays. When the amplitude of a complex-valued sequence drops below the noise floor, the phase reading becomes unreliable and susceptible to distortion. In this regime, noise dominates the measurement, resulting in phase jitter and random fluctuations that do no longer accurately represent the original signal's phase. Consequently, any phase information extracted may be incorrect, which compromises the quality of parameter extraction.

For Main bunches (indicated by red traces), an oscillation amplitude of 100 codes or higher (out of a full scale $\pm 32\,768$ codes, i.e. 0.005σ) yields a satisfactory phase reading just before turn number 15. A similar observation holds true for the Witness bunches (blue traces). The slower decay in oscillation amplitude until approximately turn 40 implies a better SNR for an extended time, during which the quality of the phase reading is also higher.

In our quest to extract accelerator parameters from the pre-processed beam position data, we focus on the delta phase value between consecutive turns. This relationship is derived in Section 3.5.1, where we introduced the instantaneous fractional tune in Equation (3.83). The results of our analysis are presented Figure 4.9, which illustrates the evolution of the bunch-by-bunch fractional tune for each individual bunch. Calculating the difference between two phase readings can amplify the effects of measurement noise at certain frequencies. As noted earlier, the fractional tune readings for red traces are quite reliable before turn number 15, while the blue traces provide good quality readings up to turn 40.

We can take advantage of this by averaging multiple readings over consecutive turns. This approach further minimizes the impact of random noise, leading to a more reliable estimate with enhanced precision for the resulting parameter reading. In the following Figure 4.10, the fractional tune for each bunch is plotted based on data averaged over 10 turns using the arithmetic mean.

Maintaining the same color coding, the blue dots represent the estimated fractional tune calculated for the Witness bunches. As a reminder, these bunches are intentionally treated by the TFB with a lower feedback gain, allowing the LHC's tune feedback system to effectively extract the fractional tune for the entire machine from these 12 bunches. As can be seen in the figure, the accelerator's tune has been well adjusted to the nominal operation value in the vertical plane, which is 0.295 at injection.

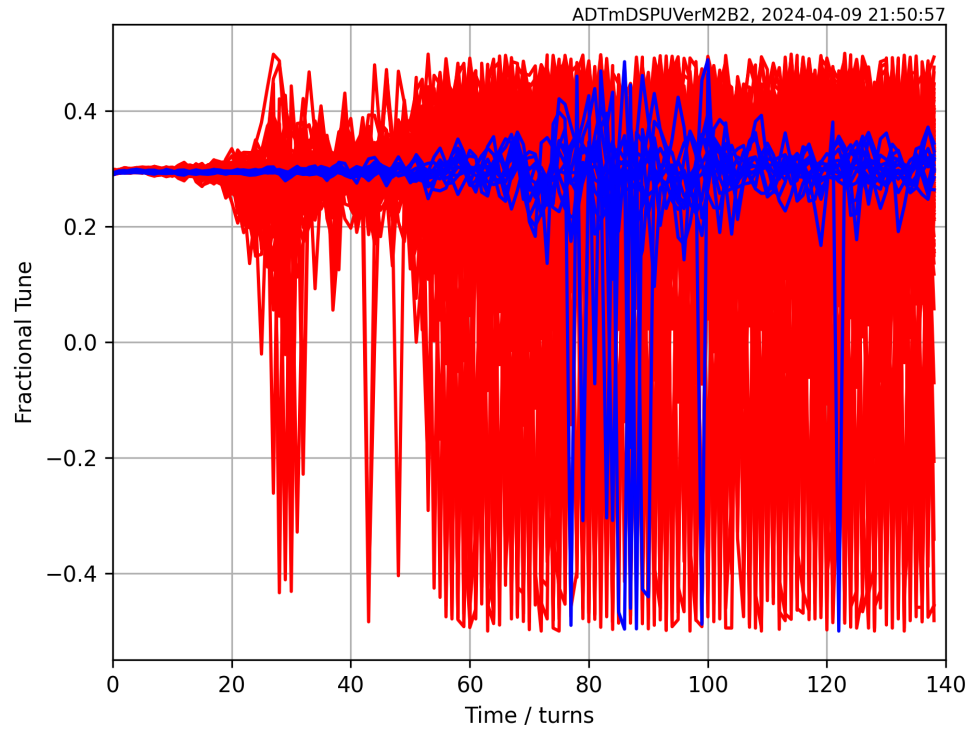


Figure 4.9: Bunch-by-bunch tune estimation from reconstructed transverse phase space. In presence of measurement noise and 0.02σ excitation, 15 and 40 turns of usable data are available for main (red) and witness (blue) bunches.

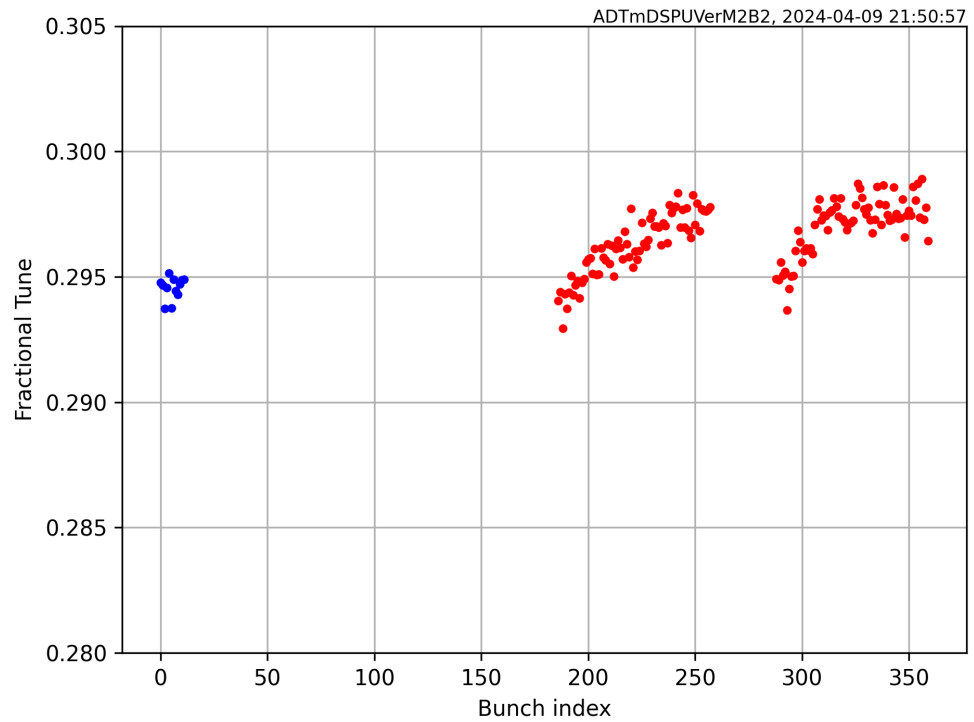


Figure 4.10: Bunch-by-bunch tune data plotted with turn-by-turn data averaged over 10 turns.

The method proposed in this thesis significantly enhances the ability to extract the fractional tune, which is now possible also for the 2×72 Main bunches (represented by red dots). The new signal processing algorithm allows accelerator physicists to visualize features along the bunch trains in a fast, simple and non-destructive manner. Notably, the initial bunches of each 72-bunch train are observed to be close to the set-point value of 0.295, while the bunches located at the end of the train exhibit a tune shift of approximately 0.002. In the context of the LHC, the high beam intensity leads to substantial collective effects, such as impedance and wakefields, which influence beam dynamics. As a result, the position of the bunches within the train starts playing a role, with the dynamics of the initial bunches differing from those of the final bunches, thereby causing variations in the fractional tune.

Recommended Feedback Phase

In Figure 4.6, we examine the phase space, where the phase is wrapped within the range $[180^\circ, 180^\circ]$. The beam oscillations recorded by the pick-up advance the phase by the fractional tune with each turn, as shown in Figure 4.9. To account for this effect, we apply a compensation, the results of which are illustrated in the left plot of Figure 4.11. This compensation is described by Equation (3.75) in Section 3.4.2, and we also incorporate the bunch-by-bunch fractional tunes identified in Figure 4.10.

By averaging multiple readings over consecutive turns we enhance the precision of our measurements. The phase advance between kicker and pick-up, measured for each bunch, is shown in the left graph of Figure 4.10. This data was averaged choosing $M = 10$ turns in Equation (3.76). The color coding is consistent with previous graphs, where blue denotes Witness bunches and red is used for Main bunches.

With the phase advance between the kicker and pick-up extracted from our measurements, we can now determine the recommended TFB phase setting for the pick-up that recorded this measurement. The feedback phase is influenced by both processing delay and group delay, each expressed in terms of the number of turns.

The processing delay refers to the time required for the system to process the signal, which is typically equivalent to a one-turn delay. In contrast, the group delay is defined by the phase rotation algorithm, specifically the time in turns needed to compute the correction based on data from previous turns. Additionally, we must take into account the phase shift introduced by the notch filter, the phase rotation necessary to convert position data to slope, and a 180° phase shift to generate a damping correction signal.

By accounting for all these factors in the context of the LHC TFB, we derive the recommended transverse feedback phase, which is the optimal setting for using this pick-up, as illustrated in

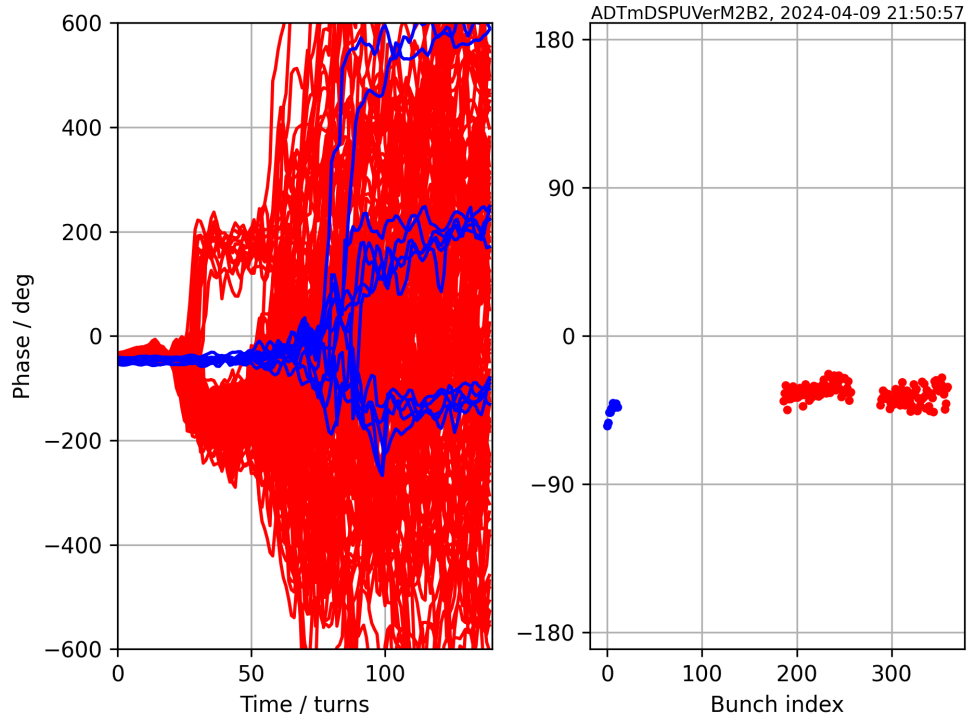


Figure 4.11: Unfolded phase from reconstructed transverse phase space on the left, with phase advance between kicker and pick-up shown on the right using averaged turn-by-turn data over 10 turns.

Figure 4.12. In this graph, the black horizontal dashed line represents the current phase setting, which aligns closely with the recommended phase for this system.

In a later step, we can profit from having several bunches generating phase readings, allowing us to derive additional statistics from this data.

A careful examination of the graph presented in Figure 4.12 reveals that the derived recommended phase is not entirely constant; rather, it varies with the the position of the bunches in the trains. This variability is not unexpected, as our investigations have shown that collective effects cause fluctuations in the fractional tune, and therefore would require a slightly different feedback phase. In light of this, it would be beneficial to consider integrating this tune dependence into the signal processing hardware as part of an upgrade scenario. This integration would involve modulating the feedback phase within a turn based on the bucket position of the bunches. This idea seems feasible, as it builds on extending the existing FPGA gateway with the proposed functionality.

Furthermore, it is essential that this feature is adjustable to accurately reflect the actual bunch intensity and filling pattern. To automate this in a practical application, a parameterized model could be employed to calculate the expected tune shift for each bunch based on its intensity—a variable that is recorded by every beam position monitor and made available as an output signal

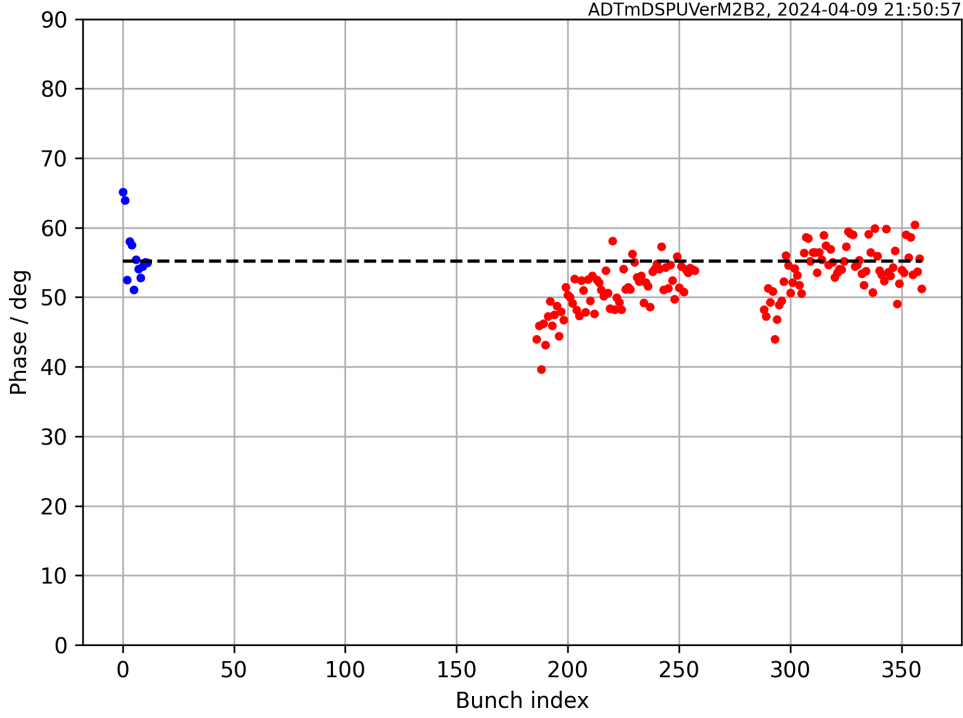


Figure 4.12: Recommended transverse feedback phase using single-turn excitation and beam position data of one pick-up.

(see Section 3.1.2).

Building on this concept, if the TFB signal processing allows for modulation of the bunch-by-bunch feedback phase, and if a parameterized model of expected tune shift per bunch intensity is developed, then the TFB could be utilized to actively counteract this tune dependence by deliberately adding a reactive component to the feedback phase. If successfully, this approach could lead to improved performance in accelerators, potentially enabling accelerator physicists to establish a constant tune that remains independent of collective effects. This proposal opens avenues for further research, such as exploring the specifics of the parameterized model, testing its effectiveness in real-world scenarios, and analyzing the implications of the findings.

Loop delay measurement method

Ensuring the stability of a Transverse Feedback system requires precise alignment of the kick signal with the arrival times of the bunches. In this section, we will outline the method introduced in Section 3.4.3, which was developed to quantify the kicker delay offset using TFB measurement data.

The projection of excitation signals encodes the time-dependence of each bunch index k as an angular position in the new coordinate system. This relationship becomes even clearer when

visualized on a polar grid, as illustrated in Figure 4.13. In this plot, each dot represents the result for one bunch based on two orthogonal excitation measurements. Dots of the same colour indicate data obtained from the same turn, and it is evident that these data points have approximately the same distance from the center.

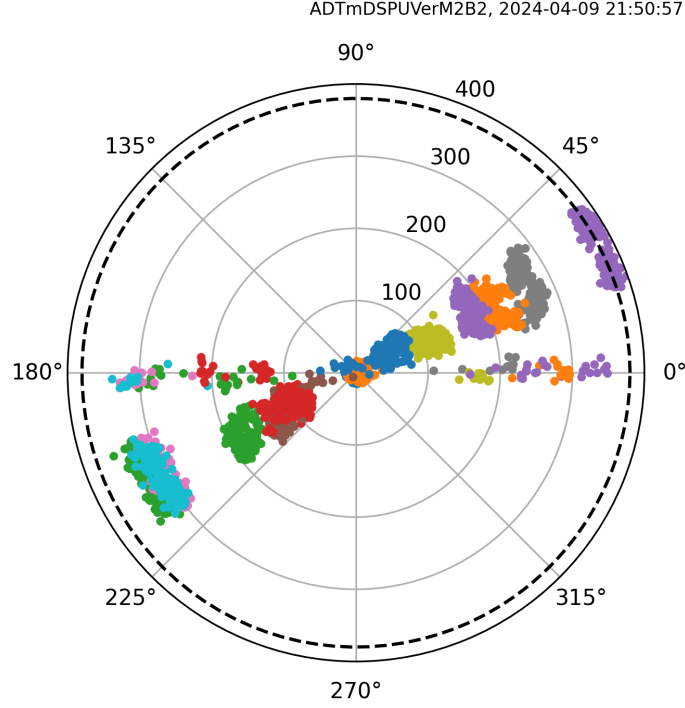


Figure 4.13: Polar grid project of bunch position signals.

Equation (3.79) suggests incorporating a linear bunch-index-dependent phase term, which allows us to unwind this phase response and align the results. As shown in Figure 4.14, this alignment produces a straight line. The parameter of interest, the delay offset ΔT , is defined by the orientation, or the phase θ , of this line (see Equation 3.80).

In Figure ??, we demonstrate the process of averaging over populated bunches. The dots in this figure represent the mean values of bunch position data at turn n , with colours indicating different pick-ups. To estimate the delay offsets, we fit straight lines through these data points. Additionally, the black dashed rays illustrate the delay error associated with the TFB coarse delay, expressed in terms of the number of buckets.

The coarse delay serves as a fundamental parameter in the TFB's digital signal processing, enabling the storage of per-bunch correction data for retrieval after a specified time interval, referred to as the one-turn delay. This functionality is realized through a First-in First-Out (FIFO) architecture implemented in the FPGA, which operates at three times the bunch rate, specifically at 120 MSPS. Consequently, each increment in the coarse delay setting corresponds

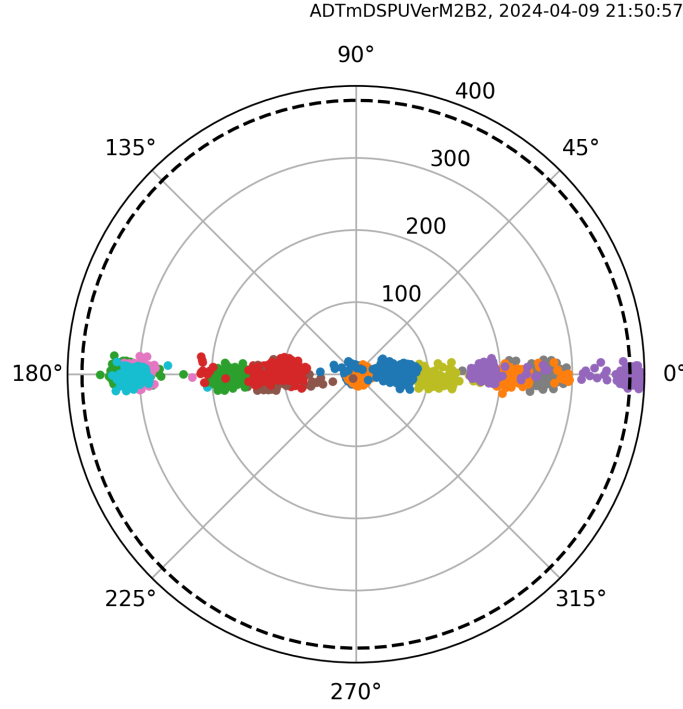


Figure 4.14: Polar grid projection of bunch position signals with bunch-index dependent phase subtraction aligning results as a line.

to a discrete time delay change of 8.33 ns. The FIFO is designed to be sufficiently large to store an entire turn of data, amounting to $3564 \times 3 = 10\,692$ values.

To further enhance measurement resolution we can manipulate the excitation parameter M . This adjustment leads to an increased sensitivity to delay offsets, a relationship that is formally expressed in Equation (3.81). The value for $M = 400$ was selected for practical reasons, it represents a trade-off between the ideal value of $M = 891$ and the first-order low-pass characteristics of the power system, which exhibits a 3 dB roll-off at 1 MHz. With the resulting excitation frequency set at 5 MHz, this configuration allows for a suitably effective kick.

For the delay analysis, each of the two recorded datasets is first baseline-corrected and the results are subsequently plotted in Figure 4.15.

The grid spacing is now defined as 1 tick, which aligns with our expectation, given that we have refined our measurement sensitivity by a factor of $M = 400$ compared $M = 1$. This enhanced resolution facilitates straightforward determination of the correct coarse delay setting. For example, in Figure 4.16, the coarse delay was deliberately reduced by 5 ticks, a change that is accurately captured by the signal processing results.

Furthermore, with additional refinement of the graphical representation of the grid spacing, the fine-delay parameter can be adjusted with sub-nanosecond precision. The analysis results presented in Figure 4.17 reflect the modified fine delay setting for this measurement.

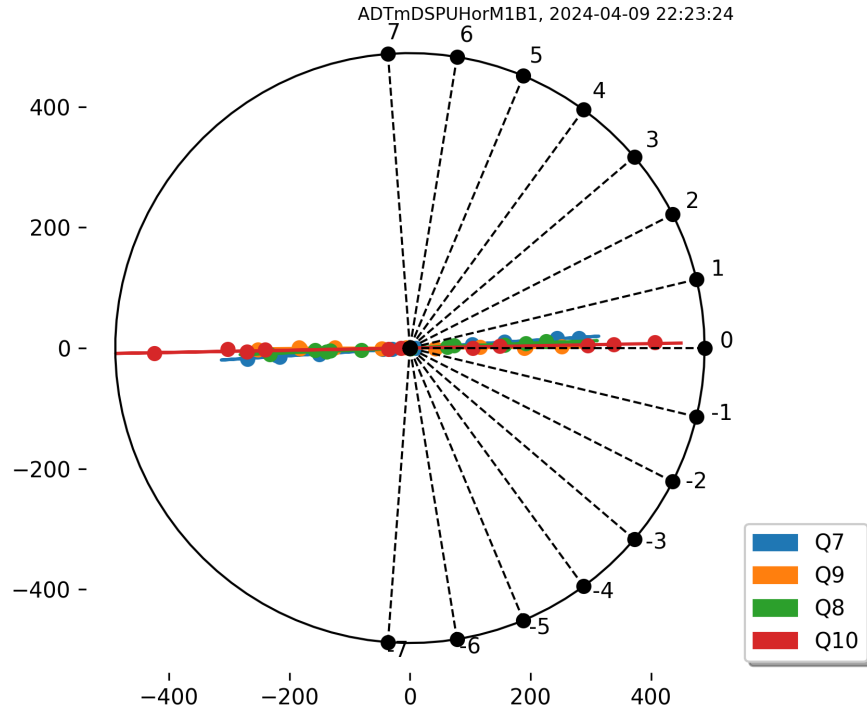


Figure 4.15: Delay analysis for $M = 400$, with rays indicating the delay error in the TFB coarse delay.

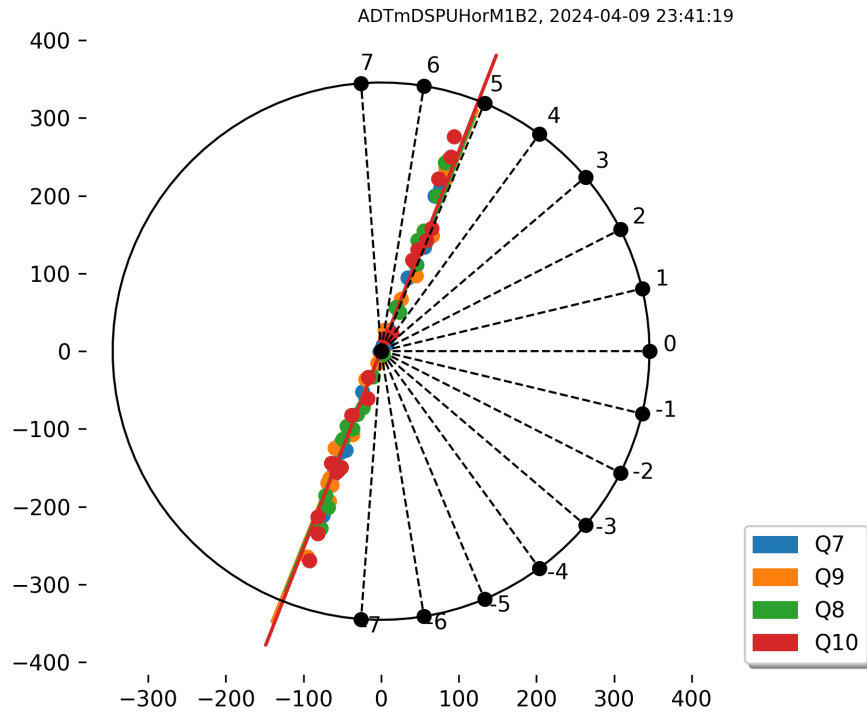


Figure 4.16: TFB coarse delay setting reduced from nominal 10 490 to 10 485; $M = 400$.

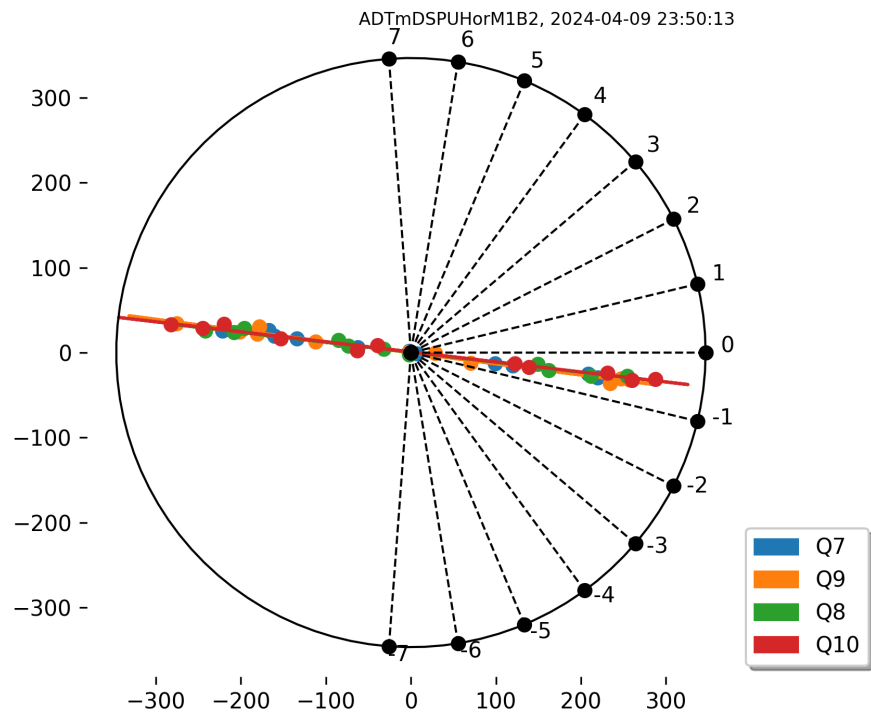


Figure 4.17: TFB fine delay setting increased by 6 8ns; $M = 400$.

4.1.2 TFB parameter measurement results

Following our detailed examination of the analysis algorithm and its sensitivity to parameter variations, this section applies the novel methods introduced for extracting essential TFB to evaluate the current performance of the system and identify potential areas for optimization. Specifically, we will analyse closed loop gain, feedback phase, and loop delay across the two distinct TFB gain regions, referred to as Main gain and Witness gain, as previously described.

Each plot presents a comparative analysis of results obtained for each pick-up, beam, module, and plane, with data from each pick-up distinctly color-coded for clarity. In every graph, we present the mean value derived from a series of measurements, accompanied with the corresponding Root Mean Square (RMS) values, which are also color-coded to align with the respective pick-ups. The black lines indicate the minimum and maximum values of the data samples, providing insights into the measurement spread and highlighting any outliers. Through this analysis, we will discuss the performance of each DSPU system, explore potential causes for deviations from nominal behavior, and identify opportunities for optimization. In all graphs the first module of Beam 2, vertical plane was offline and could not be used for data evaluations.

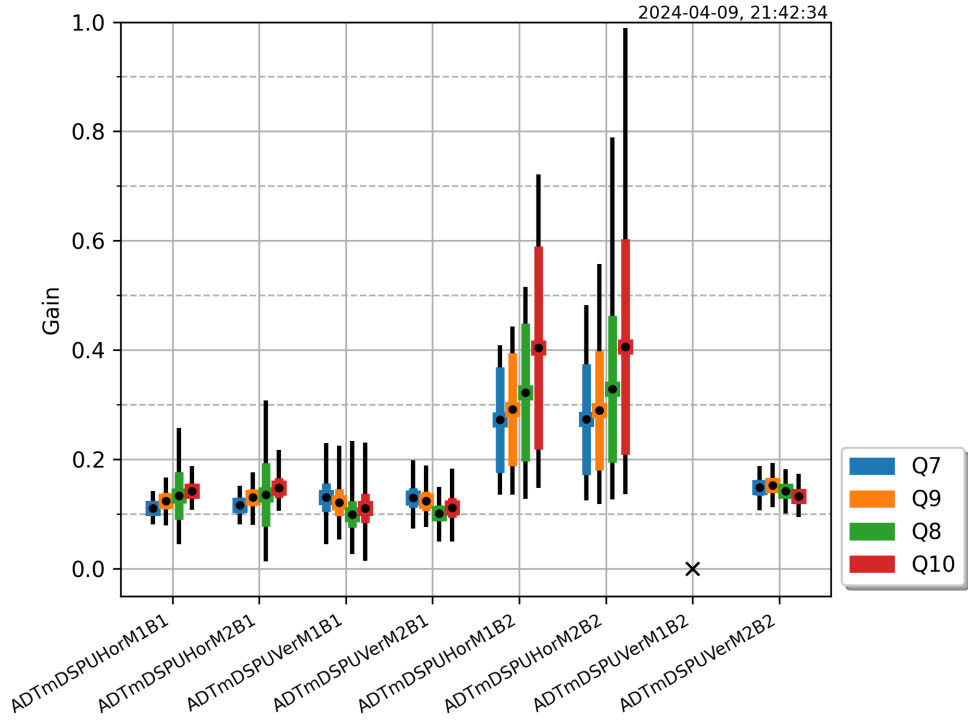


Figure 4.18: Comparison of ADT closed loop feedback gain, measured for Main Gain bunches and excitation $M=1$.

Figure 4.18 presents a comparison of the closed-loop feedback gain measured for Main bunches with excitation set to $M = 1$. The plots indicate that all modules for Beam 1 are operating within a gain range of 0.1 to 0.2, which is consistent with the performance observed for the second DSPU

module for Beam 2 in the vertical plane. Notably, the majority of the pick-ups exhibit relatively small scatter in the Root Mean Square (RMS) values and peak excursions, suggesting that the obtained results are close to the true values. However, an outlier is observed in the horizontal pick-up Q8 for Beam 1, which displays a significantly larger RMS scatter and substantial peak excursions in the measurements. Given that data from this pick-up is shared between the two concerned DSPUs, the similar results observed in these measurements imply that the issue may be related to the Beam Position Module of this pick-up or its settings.

Furthermore, a clear deviation from the nominal gain parameter is evident for both horizontal modules of Beam 2, with mean values approximately in the range of 0.3 to 0.4, accompanied by a considerably larger scatter as indicated by the RMS values. A careful examination reveals that both modules exhibit similar measurement data for the same pick-ups. It is important to note that these data are obtained through independent measurements conducted by each DSPU individually, suggesting that the observed phenomena may be related to a common factor affecting both modules.

Additionally, it is noteworthy that the loop gain is typically set by the operations group to achieve a target damping time. This indicates that these value were intentionally configured to a higher-than-usual setting. Further analysis is required to fully understand the underlying causes of these deviations and their implications for system performance.

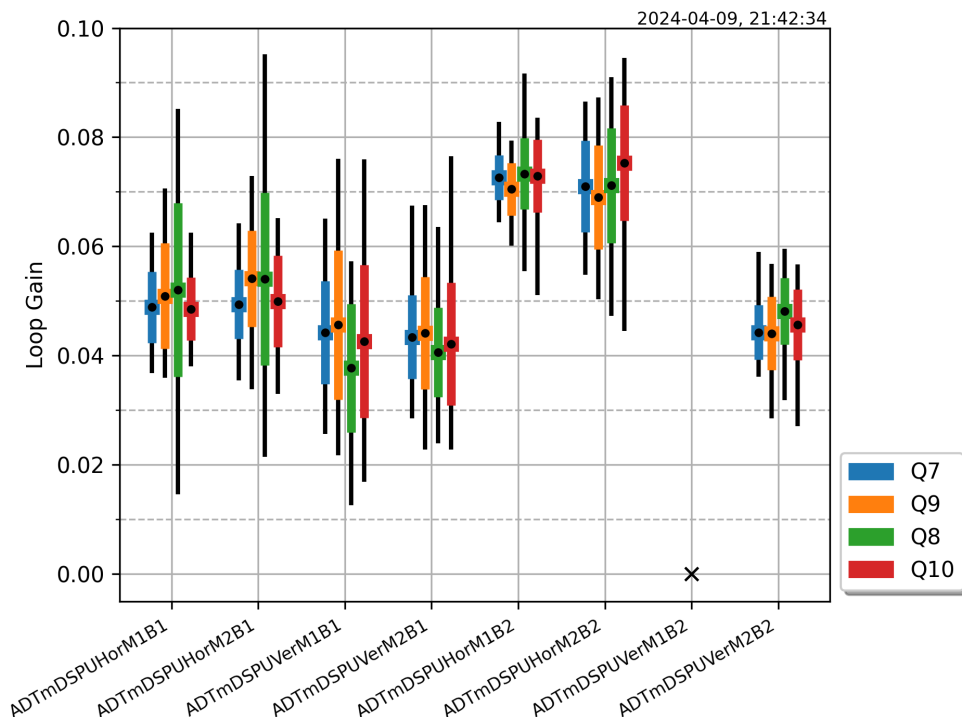


Figure 4.19: Comparison of ADT closed loop feedback gain, measured for Witness Gain bunches and excitation $M=1$.

Figure 4.19 illustrates the closed-loop feedback gain measured for Witness Gain bunches with excitation set to $M = 1$. Overall, the loop gain for these bunches is lower, typically in the order of 0.05, with the exception of Beam 2 horizontal, where the measured gain ranges between 0.07 and 0.08. Notably, the horizontal pick-up Q8 for Beam 1 exhibits a similar signature to that observed in the Main Gain analysis, characterized by large peak excursions and a comparably increased RMS spread. This consistency in behavior across different gain settings raises concerns regarding the performance of this pick-up.

Further investigations are warranted for both the Q8 pick-up in Beam 1 and the horizontal module of Beam 2 to determine the underlying causes of these anomalies and to assess their impact on overall system performance.

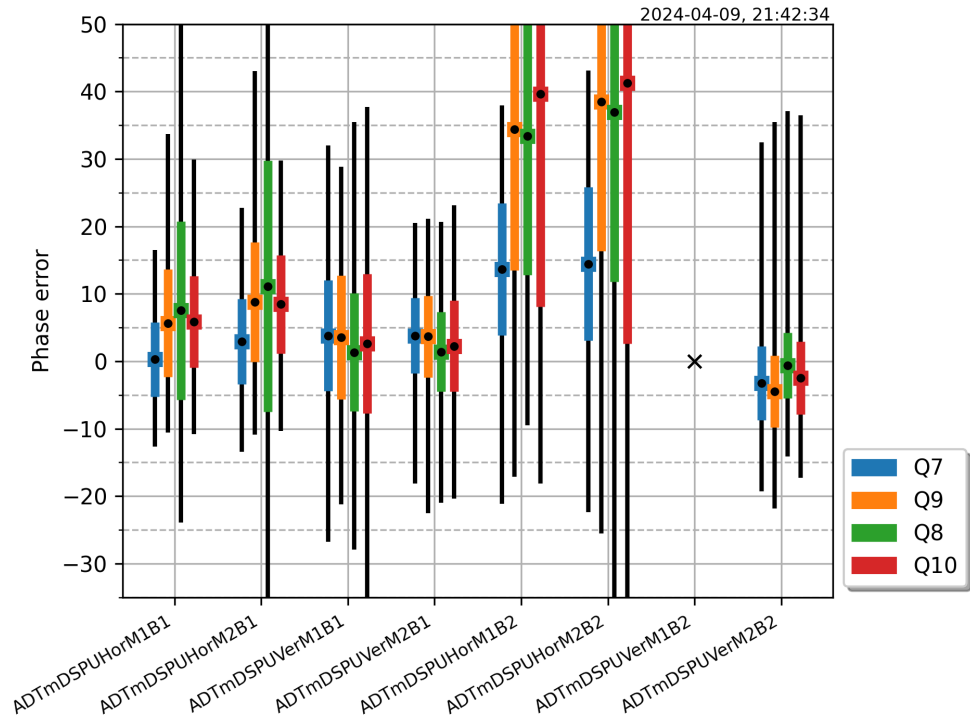


Figure 4.20: ADT feedback phase error analysis, measured for excitation $M=1$.

Figure 4.20 presents the analysis of the ADT feedback phase error measured for excitation set to $M = 1$. The graphs illustrate the phase error for each pick-up, comparing the current set point to the recommended phase setting determined by the signal processing algorithm. For the TFB systems operating Beam 1, there is overall very good agreement, with phase errors not exceeding 10 degrees and an RMS spread of only 5 degrees. However, an exception is noted for the horizontal pick-up Q8 of Beam 1, which exhibits a significant RMS spread of nearly 20 degrees and a phase error exceeding 10 degrees for module 2.

In the case of Beam 2, the typical candidates for concern are both horizontal modules. The data for pick-up Q7 indicates a phase error of 15 degrees, while the other three pick-ups show

phase errors closer to 40 degrees. The latter measurements display an RMS spread of more than 20 degrees, suggesting potential issues with the data quality of the measured input.

Conversely, DSPU Ver2M2B2 demonstrates satisfactory phase settings, with all four pick-ups exhibiting phase errors of less than 5 degrees, and a standard deviation of around 5 degrees.

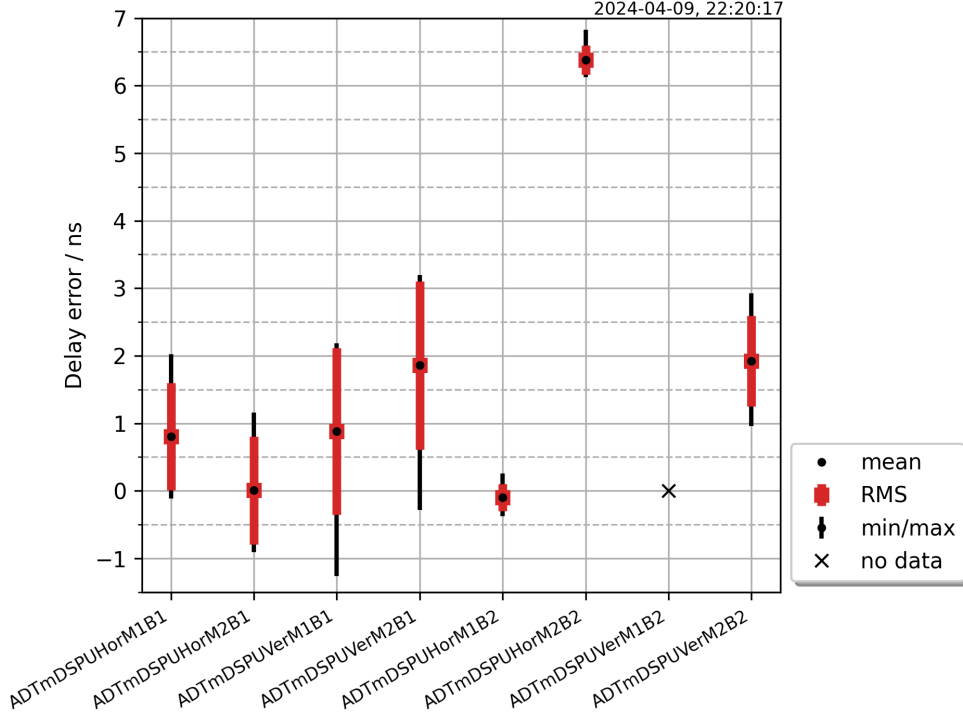


Figure 4.21: ADT fine delay error. Excitation pattern $M=400$.

Figure 4.21 illustrates the fine delay error in nanoseconds for each TFB system, with the excitation pattern set to $M = 400$. It is important to note that the delay error is related to the kicker timing, so individual measurements for each pick-up are combined to form the overall result.

for Beam 1, the delay errors are within acceptable limits, not exceeding 2 ns. Three out of four pick-ups show errors better than 1 ns, and one pick-up has nearly zero delay error. However, the standard deviation, as well as the minimum and maximum errors, are around 1 ns, indicating that the measurement distribution may not conform a Gaussian profile.

Interestingly, both modules in Beam 2 Horizontal show remarkably high data quality, with RMS values well below 0.25 ns. The delay setting for DSPU HorM1B2 is nearly optimal, while HorM2B2 has a delay error of 6.3 ns, which is significantly off target. It is important to remember that a delay error leads to a phase error. For the highest coupled bunch mode of 20 MHz in the LHC, this corresponds to $360^\circ \times 20 \text{ MHz} \times 1 \text{ ns}$, or 7.2 degrees per nanosecond. Consequently, the delay error for HorM2B2 results in a phase error of 45 degrees at 20 MHz. This significant phase error could lead to challenges, particularly when the TFB is required to counteract coupled bunch

oscillations. If one module is not properly adjusted, it will attempt to dampen these oscillations but may divide its action into two components: resistive and reactive. The reactive component could inadvertently shift the fractional tune of the already oscillating bunches

In this context, we have two redundant TFB modules operating on the same beam, both aiming to stabilize it. However, with differing system settings and parameters, these modules may compete with one another. Ideally, the performance of a well-adjusted module could help compensate for some imperfections in the other module. Overall, while the combined function of both modules may still provide damping, it is likely to be less effective than a system configured with optimal settings.

4.1.3 Accelerator parameter measurement results

In this section, we extend the analysis of TFB parameters previously conducted by employing the signal processing techniques outlined in the methods chapter to extract vital accelerator parameters from measurements. The focus will be on two key parameters: bunch-by-bunch damping time and bunch-by-bunch fractional tune, both of which are vital for assessing the performance and stability of the accelerator.

In line with the previous section, we will provide a detailed analysis for both Witness bunches and Main bunches, adhering to the same formatting conventions to ensure clarity and coherence throughout the measurement results.

It is important to note that data for the DSPU Beam 2 Vertical Module 1 is unavailable, as this module was offline during the measurement period and could not be utilized. The subsequent discussion will present the extracted parameters and explore their implications for the overall performance and stability of the accelerator system.

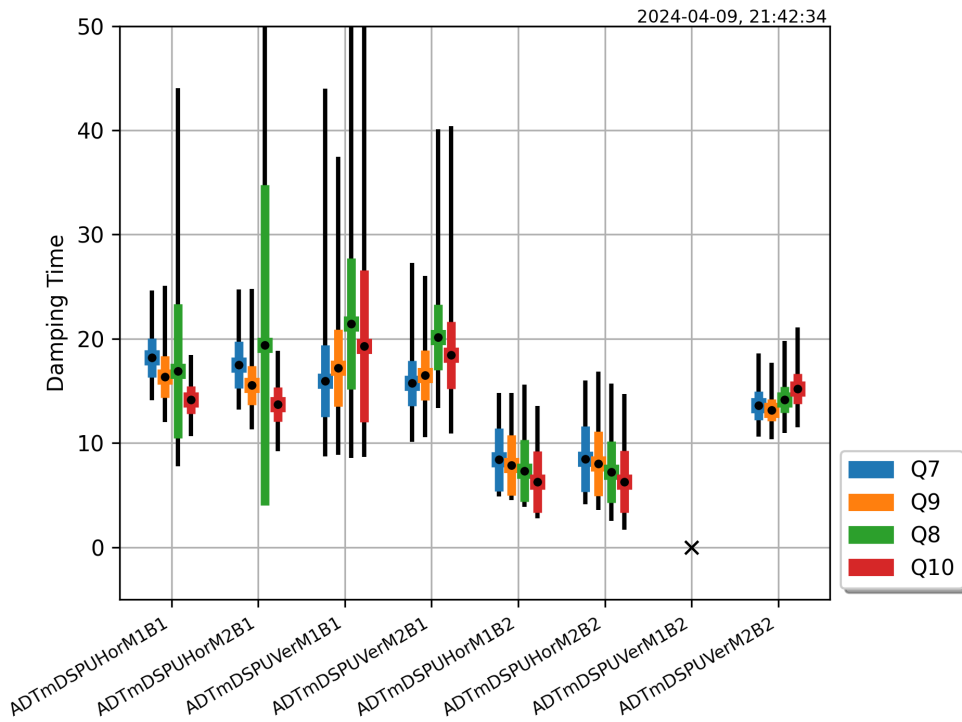


Figure 4.22: Comparison of damping time parameter for Main bunches, excitation $M=1$.

Figure 4.22 presents a comparison of the damping time parameter for Main bunches with excitation set to $N = 1$. The data for Beam 1 indicates that the Main bunches are consistently damped within approximately 15 to 20 turns, based on the assumption that the oscillation amplitude follows an exponential decay. The damping time measurements for all modules were conducted with one module operating in open loop and the other in closed loop mode.

Among the recorded measurement samples, pick-up Q8 of Beam 1 in the horizontal plane exhibits a significantly larger standard deviation compared to the other pick-ups. This is consistent with our previous observations, suggesting that the greater variability may be due to data quality issues of the Beam Position Module.

In contrast, the two horizontal modules of Beam 2 demonstrate notably higher performance, achieving damping times below 10 turns. In this regime, the TFB exerts a strong influence on the beam; however, it is important to note that such strong damping can lead to overdamping, which is generally undesirable. Overdamping may adversely affect beam stability and overall performance, making it imperative to evaluate the time evolution of the oscillation amplitude.

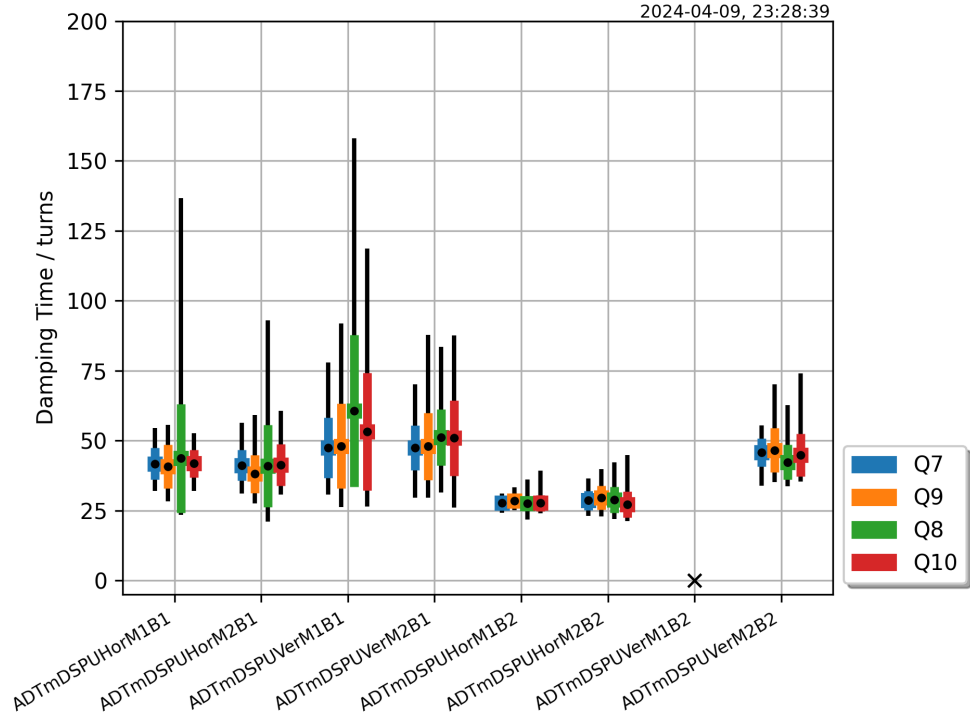


Figure 4.23: Comparison of accelerator damping time parameter for Witness bunches, excitation $N=1$.

Figure 4.23 presents a comparison of the accelerator damping time parameter for Witness bunches with excitation set to $M = 1$. The damping times for the Witness bunches are observed to be in the range of approximately 40 to 50 turns. This analysis indicates that the damping times for Witness bunches are notably longer compared to those of the Main bunches, which is an expected and intentional behavior. This extended damping time facilitates the LHC's BBQ system in accurately detecting the fractional tune in the presence of a strong transverse feedback system.

However, an exception is noted in the horizontal plane of Beam 2, where both modules exhibit significantly shorter damping times, close to 25 turns.

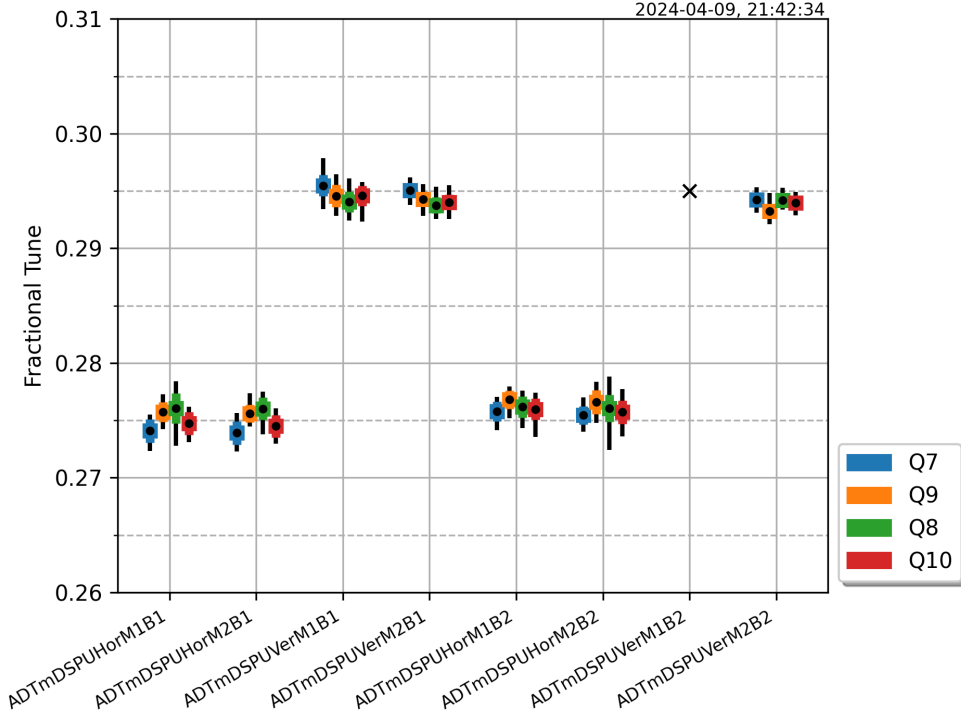


Figure 4.24: Evaluation of accelerator fractional tune parameter for Witness bunches (excitation $M=1$).

Figure 4.24 presents the evaluation of the accelerator fractional tune parameter for Witness bunches with excitation set to $N = 1$. The results obtained from this analysis highlight the effectiveness of the novel algorithm employed to measure the fractional tune using only a limited number of turns of observation data. Notably, the measurements exhibit very little scatter, with RMS values well below 0.001, demonstrating remarkable precision in detecting the fractional tune.

The reduced TFB gain for these bunches further enhances the measurement results, allowing for more accurate readings. The machine appears to be correctly adjusted for the nominal fractional tune values, which are 0.275 in the horizontal plane and 0.295 in the vertical plane. This alignment with the expected values underscores the algorithm's capability to accurately capture the fractional tune.

Figure 4.25 presents the evaluation of the accelerator fractional tune parameter for Main bunches with excitation set to $M = 1$. Consistent with the results obtained for the Witness bunches, a distinct separation between the horizontal and vertical tunes is observed. The measured tune values for these high-intensity trains indicate a positive tune shift of approximately 0.005 when compared to the values recorded in the low gain region. Furthermore, the RMS values of 2.5×10^{-3} confirm the good resolution of the measurements.

The mean fractional tune values extracted from four different pick-up datasets per DSPU are closely aligned, which is desirable since these pick-ups are intended to measure the same

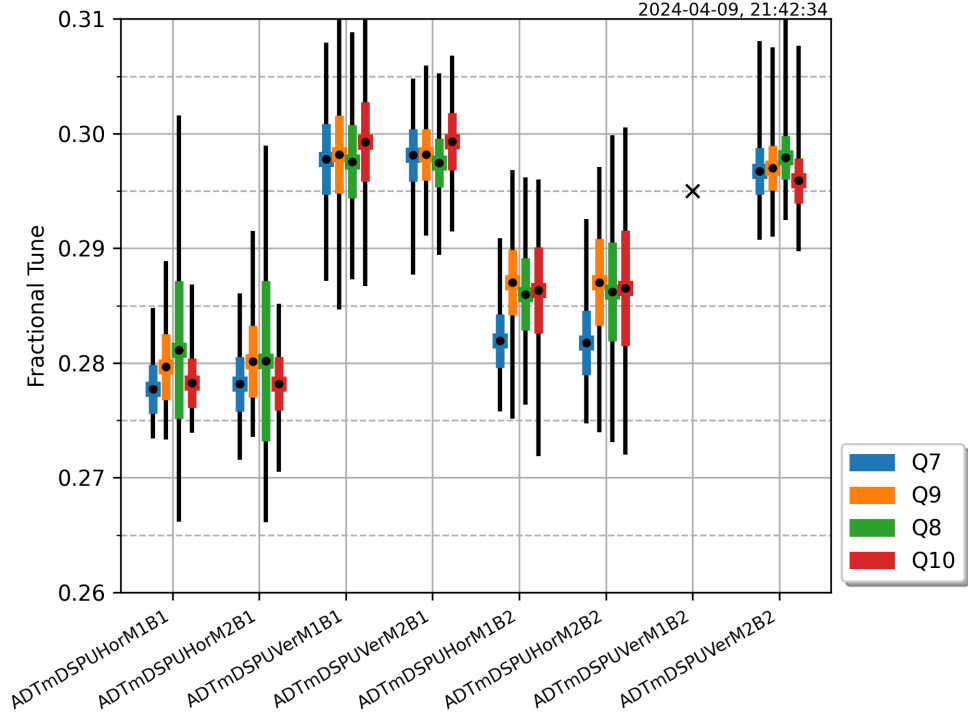


Figure 4.25: Evaluation of accelerator fractional tune parameter for Main bunches (excitation M=1).

property of the beam independently and at different locations within the machine. However, an exception is noted in Beam 2 in the horizontal plane, where three out of four pick-ups report similar mean values, with a significant tune shift to 0.287, while the expected value, as indicated by the Witness bunches, is 0.275. The fourth pick-up, Q7, displays a notable deviation, with a delta value of -0.005, leading to a tune estimation closer to 0.282. This atypical data raises concerns, as all pick-up acquisitions are triggered by the same excitation pulse, and the betatron tune oscillations (the number of oscillations per turn) for this beam are expected to be consistent across measurements.

The irregularity observed in pick-up Q7 of Beam 2 in the horizontal plane is supported by two independent measurements from DSPU module 1 and DSPU module 2. One possible explanation for this discrepancy may be a misconfiguration of the corresponding beam position module. Therefore, further investigations into the DSPUs for Beam 2 and their associated Beam Position Modules in horizontal are recommended to address these anomalies.

4.2 Extraction of vital accelerator parameters in real time

The reconstructed phase space of the circulating beam allows to extract in real time the

transverse activity of each individual bunch. Of large interest for the machine operation is the oscillation amplitude and its evolution over time. After the method was introduced [75] a very primitive proof of principle application (shown in Figure 4.26) was presented to the LHC operations group.

The demonstrator quickly became an operational tool, where a detailed transverse activity of the beam can be observed through the whole cycle. This method and the resulting tool actually changed the view on how the LHC should be operated. Some of the transverse instabilities at particular points in the machine cycle, which were originally expected by the accelerator and beam physics group have not developed. And at the same time, an increased transverse activity had been observed where it was not expected at all, triggering investigation on the possible sources and mitigations.

Figure 4.27 shows a detail of transverse activity for one 48-bunch train circulating in the slots 1570 to 1618. The actual transverse oscillation amplitude is in order of $1\text{ }\mu\text{m}$, but an excess of $40\text{ }\mu\text{m}$ was recorded as a consequence of the injection kicker waveform leakage to the turn.

Figure 4.28 shows a peak activity of all bunches during one full LHC machine cycle. The injection started at around 8:20, the energy ramp around 8:50, the top energy was reached shortly after 9:00. The two beams were put into collisions shortly after, this is where the transverse activity diminishes due to the stabilizing effect of the colliding beams.

Figure 4.29 shows another application, used operationally in the LHC control centre. The plots show bunch by bunch damping time and tune, extracted from the injection oscillation transient. It provides a quick check if the TFB is operating properly (Is the damper damping? question). The application is extremely useful at the LHC restart after a long technical stop, or a shutdown. Provided the LHC TFB pickups are properly set-up, what is usually the case, the operators will instantly get the tune value of the virgin machine which was just powered up, from the very first few turns the beam will make in the LHC. The beam does not even need to be captured yet, it is sufficient if it makes as few, as 3-5 turns before it debunches and the tune value can be measured by the TFB. The operators immediately have the initial tune value and quickly calculate and apply the tune correction. The next injection is already very close to the nominal. This saves hours of precious machine time at every start up.

4.3 Digital filter design to reduce tune dependence

In this section, we present the findings related to Objective #5, which focuses on the development of advanced signal processing techniques aimed at enhancing the robustness of transverse feedback systems in the context of tune variations. Our emphasis is on Finite Impulse Response

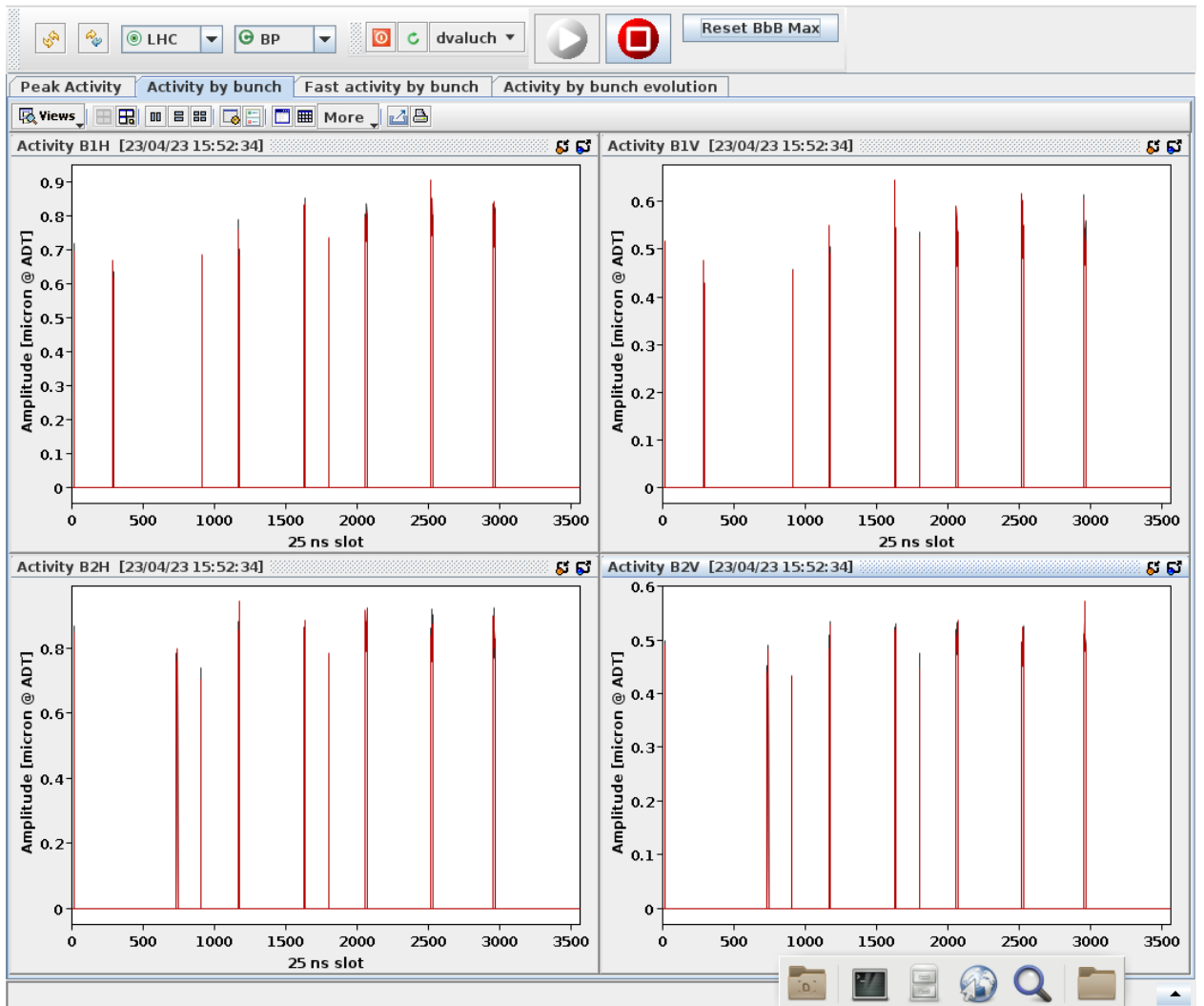


Figure 4.26: Display application for real time transverse activity monitor used in LHC

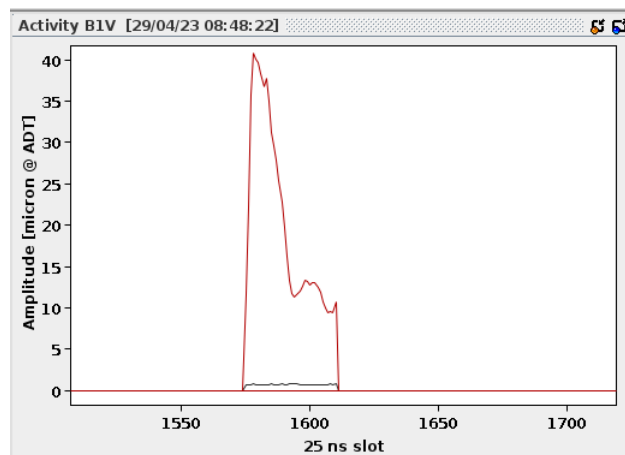


Figure 4.27: Detail of a real time transverse activity for one 48-bunch long bunch train

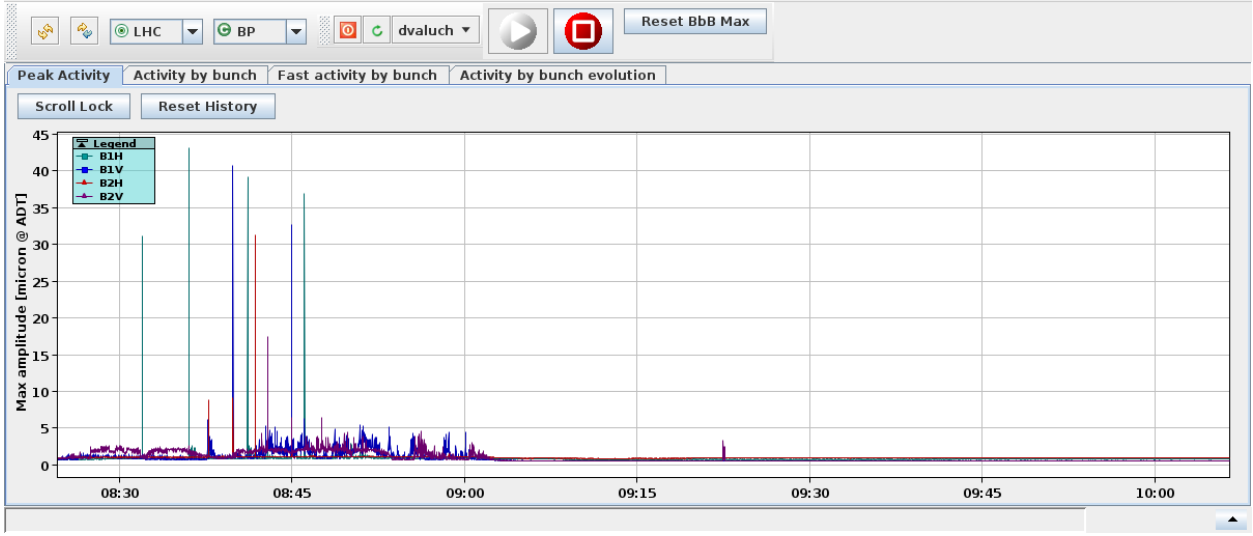


Figure 4.28: Overall transverse activity through one LHC fill.

methods, specifically tailored to address the challenges posed by frequency-dependent phase variations.

As any regulation loop, the TFB signal processing chain is constrained by the accuracy of external parameters like the phase margin, gain margin, and stability of the loop delay. In an accelerator, those parameters are often changing with the machine parameters, like tune variation or hardware changes like tetrode burn out and aging. Aim of the objective #5 is to design a new signal processing scheme, or filters, which will reduce dependence of the TFB performance on external parameters variations. The priority is to relax the tune dependence. The LHC, when in collisions, is operated with a large bunch by bunch tune spread. The feedback must be able to treat all bunches equally to prevent unwanted selective emittance growth, or trigger an onset of transverse instability for certain bunches.

As presented in [76], the introduced beam model of transverse oscillations in equation (3.25) allows numerical evaluation of the analytic expressions for the described phase adjustment possibilities. We use root locus plots to study the evolution of the beam's closed-loop poles at selected frequencies, $\omega_0 = 2\pi Q_f$, and as a function of the feedback gain.

Considering equation (3.52) for the use with arbitrary fractional tunes: the same Pick-up Vector Sum algorithm 3.50 as for the two pick-up case can be applied for a single pick-up at subsequent turns, as outlined in Fig. 4.30. In this case we define $\phi_1 = 0$ and $\phi_2 = 2\pi Q_f$, to be used with Eq. (3.50) respectively Eq. (3.51).

Figure 4.30 suggests that by considering a notch filter using $h[n] = [1, -1]$ the phase shift between $y_k[n]$ and $p[n]$ can be carried out by a short FIR, with the filter coefficients resulting from

$$y_k[n] = b_1 p[n] + (b_2 - b_1) p[n - 1] - b_2 p[n - 2]. \quad (4.1)$$

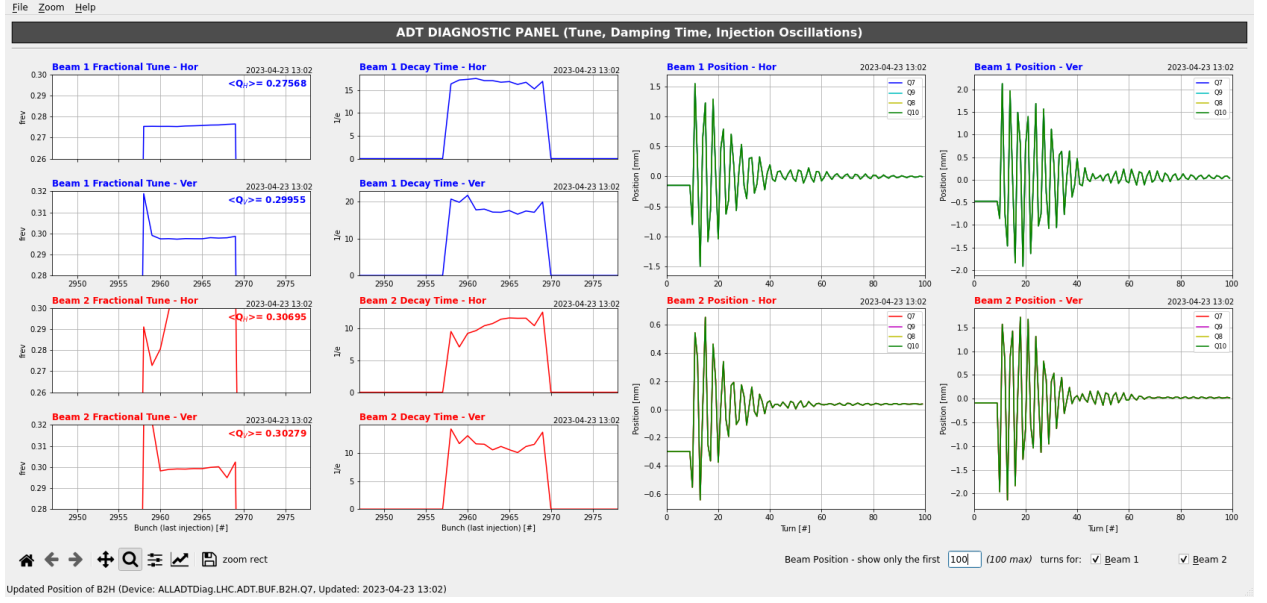


Figure 4.29: Display application showing extracted machine parameters (tune) and transverse feedback parameters (damping time) in LHC

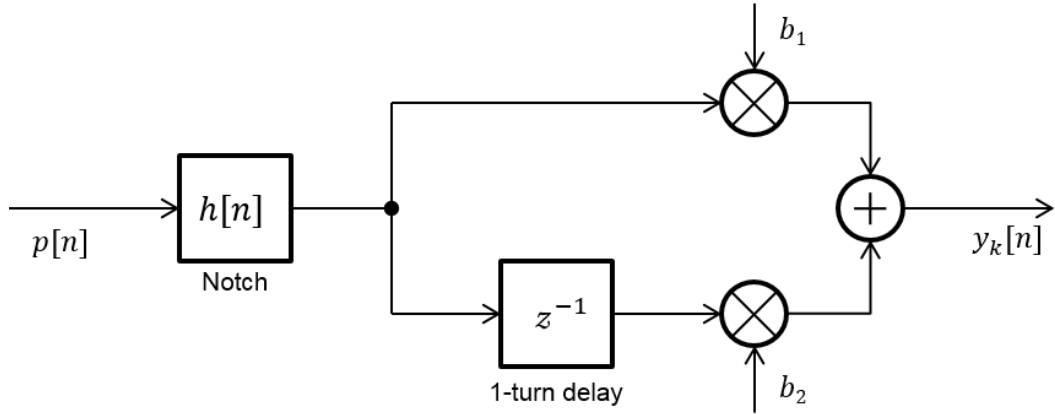


Figure 4.30: Block diagram of temporal phase shift.

With only three taps and including a notch for DC-orbit suppression Eq. (4.1) describes the shortest possible digital filter. The design has two parameters, the fractional tune Q_f and a free parameter ϕ_k which allows for direct phase adjustment.

Optionally, improved noise suppression can be achieved with zeros added at $z = \pm 1$, which can be absorbed into the notch filter, $h[n]$, including an extra phase term, $\Delta\vartheta = -\pi Q_f$ into Eq. (3.51) for every additional tap the notch filter is extended.

The three plots in Fig. 4.31 detail a portion of the upper right quarter of the complex z -plane. As an example closed-loop pole trajectories for the SPS vertical plane are shown, assuming a fractional tune of $Q_f = 0.18$ and variations of up to ± 0.04 (blue, solid). Their origin is at the unit circle (black, bold solid) for zero loop gain (corresponding to the undamped open loop response). By increasing the feedback gain the damping time reduces gradually until the trajectories cross

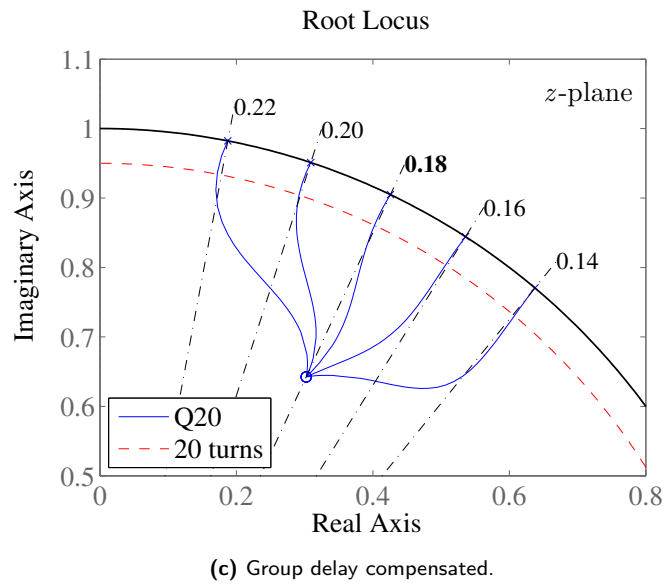
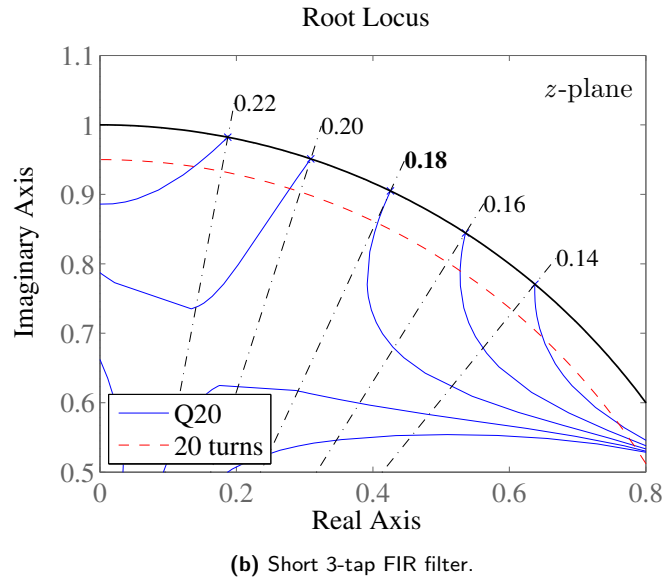
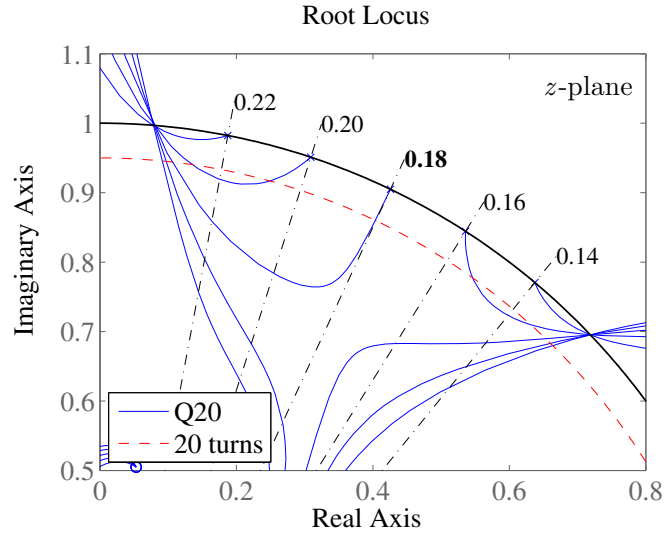


Figure 4.31: Root locus plots, fractional tune $Q_f = 0.18 \pm 0.04$

the circle at $|z| = 0.95$ (red, dashed) which is the design value of the SPS TFB corresponding to 20 turns. For as long as a trajectory points towards the origin of the z -plane (black, dash-dotted lines) it will follow the desired closed loop negative feedback of -180° .

Figure 4.31(a) shows the beam response for a standard FIR Hilbert phase filter, using seven taps for the case of the SPS TFB. As can be seen this filter is working perfectly fine at the target tune of 0.18, however, the feedback phase appears to be sensitive to tune variations, with the active feedback adversely pushing the tune further away the more its value deviates from the desired value. This effect is attributed to the constant group delay of the FIR filter causing the feedback phase to be optimum only for a single frequency and to roll off quickly for long filters.

The shortest possible digital filter including a notch for DC-orbit suppression will only include three taps. The design has two parameters, the fractional tune Q_f and a free parameter ϕ_k which allows for direct phase adjustment. Shortening the FIR filter length to only 3 taps, has a positive effect on tune variations, as can be seen by inspecting Fig. 4.31(b), with the closed loop response remaining stable over a larger range of tune values.

By anticipating that the group delay — a measure for linearity of the phase — introduced by a filter lowers the stable phase margin of a closed loop system we made an attempt to compensate this effect by introducing an additional pair of conjugate complex zeros, $c_{1,2} = \zeta e^{\pm j\omega_d}$, at the desired tune frequency, $\omega_d = 2\pi Q_f$, which adds negative group delay as a function of the magnitude, ζ . The group delay as specified in Ref. [68] follows for a direct-form FIR transfer function as

$$\tau(\omega) = - \sum_{k=1}^M \frac{|c_k|^2 - \Re\{c_k e^{-j\omega}\}}{1 + |c_k|^2 - 2\Re\{c_k e^{-j\omega}\}}. \quad (4.2)$$

By taking into account the secondary phase term resulting from these zeros the overall group delay was compensated to $\tau(\omega) = 0$ at the design tune, $\omega = \omega_d$. Note that a system having zero group delay is able to transmit the signal's envelop without delay. Figure 4.31(c) shows that the loop stability is ultimately improved by carefully compensating the group delay of the digital filter. With its flat phase response around the design tune this filter is robust against changes of the fractional tune in the order of $\pm 22\%$. This filter was tested in the SPS TFB by changing the machine's fractional tune and performing beam transfer function measurements. The results listed in Table 4.1 confirm the theory of negative feedback over the same range of fractional tunes.

Table 4.1: Measured loop response vs. tune.

Tune	0.14	0.16	0.18	0.20	0.22
Phase	-167°	-179°	-182°	-182°	-187°

New FIR phase shift filters have been designed and analysed for the SPS TFB based on a simple beam model in z -domain and with root locus plots, to assess their closed loop performance with beam and in presence of active feedback. The obtained results were found to be in good agreement with measurements carried out in the SPS. Limitations on system gain [79], the performance in the presence of noise [80, 81], and the ability to reject disturbances are subject of further studies.

The shortest digital filter described has only 3-taps, including DC suppression by a notch filter (for other realisations of short phase shift filters see for example [82–87]). Moreover, the tune sensitivity was further compensated with an additional pair of conjugate complex zeros, effectively lowering the filter’s group delay to zero at the fractional tune. Compensation of tune-dependent phase variations were reported also in Ref. [88].

The described digital filters are reasonable candidates for replacing the Hilbert phase shifter currently in use in the transverse feedback system of the SPS, mostly due to their favourable response over a larger range of tune values.

Results and Discussion

The effective operation of transverse feedback (TFB) systems is critical for maintaining the stability and performance of particle accelerators. A recurring inquiry from the operations group has been: *Does the TFB work as intended?* This thesis aims to provide means to quickly answer this question by defining methodologies to extract important TFB and the accelerator parameters using exclusively the TFB itself and observables available in the TFB system.

By developing robust signal processing techniques and analysis algorithms, this research aimed to create a comprehensive theoretical framework, supported by experimental data, that accurately evaluate the performance of TFBs. The goal was to develop practical methods that enable real-time measurement of TFB parameters during accelerator operations.

Traditional feedback parameters extraction techniques often rely on external instruments, which are time-consuming lack accuracy and compromise beam stability. In contrast, this research explored the potential for feedback parameter extraction and performance optimization through active beam manipulation using only the TFB system. The study examined various factors that affect TFB performance, including loop gain, feedback phase, delay, and processing noise, and proposed methods for quantifying these parameters to enhance real-time verification of TFB performance.

Furthermore, the research investigated extraction of key accelerator parameters, such as bunch-by-bunch machine tune and damping time, from observable quantities within the TFB system. This approach addresses operational concerns while contributing to a deeper understanding of the TFB's impact on the overall accelerator performance.

The following sections discuss the implications of these findings and highlight their importance for the operations group and the further development of TFB systems in particle accelerators.

Key findings

This study provided several important insights into signal processing techniques for transverse feedback systems in hadron accelerators. The advances made in this research are summarized below and divided into individual findings that improve the verification and optimization of TFB performance:

Finding #1: *The simplified z -domain beam model enables the application of digital signal processing methods in beam dynamics.*

This research demonstrates that the development of a simplified beam model in the z -domain represents a significant advance in the application of digital signal processing methods within this area. This model simplifies the analysis of beam dynamics and improves the applicability of sophisticated signal processing techniques, thereby facilitating real-time performance verification of TFB systems.

Finding #2: *The analytical sensor model enables the practical implementation of realistic LHC TFB behaviour in particle tracking code.*

This research demonstrates the significant importance of developing an analytical model that describes the relationship between the transverse beam position and the generated output. It enables the realistic implementation of the transverse feedback behavior of the LHC and SPS in particle tracking codes. This is crucial for investigating beam stability and ensuring low emittance bunches in high-energy physics experiments.

Finding #3: *Analytical modeling of the sensor and actuator confirmed their ability to process bunches independently.*

This research demonstrates that a thorough analysis of the beam position sensor and actuator provides important insights into their performance. The hardware implementation has demonstrated its ability to treat bunches independently, thereby minimizing inter-symbol interference and ensuring accurate measurement and control of individual bunches.

Finding #4: *Novel methods for real-time reconstruction of transverse phase space coordinates for individual bunches.*

This research demonstrates advances in the understanding and application of phase adjustments in beam position signal processing. The proposed interpretations of spatial and temporal phase shifts create a robust framework for converting beam position signals into transverse phase space coordinates, thus enabling effective real-time performance monitoring.

Finding #5: *Definition of new signal processing methods for measuring key feedback parameters.*

This research demonstrates the development of a comprehensive method for extracting feedback parameters, thus fulfilling the need for practical measurement techniques in accelerator operation. By exploiting single-turn transverse excitations generated by the kicker of a transverse feedback system, real-time monitoring and adjustments become possible.

Finding #6: *Advanced signal processing techniques for extracting vital accelerator parameters.*

This research demonstrates that innovative methods for extracting vital accelerator parameters from observables within the transverse feedback system have been established. The ability to measure machine tune and damping time in real-time, bunch-by-bunch, significantly improves operational capability and contributes to a deeper understanding of the TFB's impact on accelerator performance.

Finding #7: *Transverse phase space reconstruction methods require signal-to-noise ratio (SNR) of at least 30 dB to resolve tune variations of better than 10^{-3} .*

This research demonstrates that noise management is critical for accurate measurements and real-time performance verification, as the effectiveness of transverse phase space reconstruction methods decreases in noisy environments.

Finding #8: *The ADTObBox system is equipped with advanced computational capabilities and efficient algorithms to support real-time data processing and high-performance analysis.*

This research demonstrates the need to implement efficient algorithms that can operate in real-time processing environments to improve the verification of TFB performance.

Finding #9: *The influence of short transverse excitations on beam size is negligible when a strong transverse feedback system is present.*

This research demonstrates that numerical simulations indicate minimal to no increase in transverse emittance at the current damping time of the LHC TFB. This enables routine measurements without compromising beam quality.

Overall, these results represent a significant contribution to the understanding and performance of transverse feedback systems in particle accelerators. They highlight both methodological advances and their practical implications for improving accelerator operations in real-world environments.

Interpretation of findings and significance of obtained results

The results of this study have important implications for the field of transverse feedback systems in particle accelerators. A key advance is the introduction of a simplified beam model in the z -domain. This model improves the application of digital signal processing methods and facilitates access to advanced techniques for real-time performance verification of TFB systems. By more efficiently analyzing beam dynamics, it facilitates the use of sophisticated control engineering tools.

Another important insight comes from the development of an analytical model for LHC and SPS transverse feedback behavior. This model enables realistic implementations in particle tracking codes, which are crucial for studying beam stability and maintaining low emittance bunches. The ability of the sensor and actuator to treat bunches independently with minimal interference ensures accurate measurement and control, a vital achievement for high-energy accelerators.

Furthermore, the novel methods for real-time reconstruction of transverse phase space coordinates provide immediate insights into beam behavior. This enables operators to make informed decisions for performance optimization and mitigation of potential instabilities, thus significantly increasing the operational efficiency of particle accelerators.

A significant contribution of this study is the introduction of the concept of transverse activity, a novel metric that measures the instantaneous oscillation amplitude of the beam. This quantity not only facilitates the derivation of decay rates and TFB gain from transverse activity but also provides immediate diagnostics for transverse instabilities. Such instabilities can significantly impact the performance and safety of accelerator operations, making this diagnostic capability particularly valuable.

Based on this, we have introduced a method for calculating the TFB phase advance between the kicker and the pick-up following a single transverse kick. This method allows for immediate and non-destructive analysis of TFB phase settings, which is crucial for real-time monitoring and optimization of transverse feedbacks in accelerator environments.

Furthermore, we have presented a new technique for quantifying the kicker delay offset using TFB measurement data. By employing modulated kick data in quadrature, we constructed an IQ-footprint of the traversing bunches, allowing for the extraction of the delay offset. Our findings demonstrate accurate measurements of the TFB delay with sub-nanosecond precision. This level of accuracy is essential for fine-tuning TFB systems and ensuring optimal performance.

Furthermore, the ability to measure machine tune and damping time in real time on a bunch-by-bunch basis from the internal TFB signals represents a significant advance in accelerator

systems technology. This granularity enables a more detailed understanding of accelerator performance and can lead to improved stability through adaptive control mechanisms.

Of particular note are insights into the signal-to-noise ratio requirements for capturing a transverse oscillation amplitude. The requirement of a minimum SNR of 30 dB to resolve tune variations underscores the importance of noise management in beam diagnostics. These findings are crucial for the development of future measurement systems and emphasizes the need for robust signal processing techniques that operate effectively even in challenging environments.

The conclusion that short transverse excitations in the presence of a strong TFB system have a negligible impact on beam size suggests that routine measurements can be performed without compromising beam quality. This finding supports the integration of regular evaluations into operational protocols and enables proactive monitoring of TFB performance.

Using these novel techniques, a full set of measurements to characterize the TFB system in CERN's LHC, comprising of 16 pick-ups and 8 signal processing units, takes less than a minute. The proposed techniques allow us not only to shorten the TFB commissioning time from several shifts to less than a minute but also regular, fully automated checks of TFB system can now be performed in case of suspected suboptimal performance, saving significant amounts of precious machine time.

Conclusions

This study introduced a number of novel techniques and methods to the field of transverse feedback systems in particle accelerators, particularly in the context of hadron accelerators. By developing innovative signal processing techniques and analytical models, we have improved the understanding and application of transverse feedback systems. This research addresses critical questions about their performance and functionality, paving the way for improved accelerator operation. Many of the techniques are already implemented in accelerators at CERN and being routinely used in operation. Stable beam and optimally functioning transverse feedback is the best proof that the presented techniques and novel approaches are sound, and very valuable for the accelerators.

One of the most important findings of this study is the introduction of a simplified beam model in the z -domain, which facilitates the application of digital signal processing methods in beam dynamics. This advance not only simplifies the analysis of beam behavior but also improves the integration of sophisticated techniques into real-time systems, thus increasing operational efficiency.

Furthermore, the development of an analytical sensor model enabled the realistic implementation of transverse feedback behavior in particle tracking codes, which is essential for investigating beam stability in high-energy physics experiments. The ability to treat bunches independently, as confirmed by our analytical modeling of sensors and actuators, underscores the robustness of the TFB system and its optimization potential.

The novel methods for real-time reconstruction of transverse phase-space coordinates represent a significant advance in operational capabilities. By enabling immediate diagnostics and adjustments, these methods enable operators to increase performance and effectively minimize instabilities.

Furthermore, the comprehensive approach to measuring key feedback parameters and vital accelerator parameters opens new avenues for research and operational improvements. The results suggest that real-time monitoring and adaptive control mechanisms can be implemented to optimize accelerator performance, thus ensuring stability and efficient operation. The focus of

the work is on finding a simple, well-defined parameter or method that provides clear answers to operational questions, such as: *Is the damper damping?* The research presented here contributes to this goal by developing methods that provide the positive answer, *Yes, the TFB is functioning properly and the damper is damping.* These practical insight are crucial for the operations group, enabling informed decision-making and ensuring optimal performance in complex accelerator environments.

In summary, this research not only addresses the operational aspects of TFB systems but also contributes to a deeper understanding of their impact on accelerator performance. The presented methods and insights lay the foundation for future advances in TFB technology and its applications in particle accelerators. Future research should focus on the broader applicability of the developed models and techniques in different accelerator environments. Investigating the integration of these methods into existing feedback systems, as well as exploring their potential for real-time adjustments, will be crucial for the further development of this research area. By further refining and expanding these insights, we can further improve the performance and reliability of particle accelerators and ultimately contribute to the advancement of high-energy physics research.

All research objectives of this thesis were fully met.

Zhrnutie dosiahnutých výsledkov

Efektívna prevádzka systémov s priečnou spätnou väzbou (transverse feedback, TFB) je kritickej pre udržanie stability a výkonu urýchľovačov častíc. Opakujúca sa otázka od prevádzkovej skupiny je: *Funguje systém s priečnou spätnou väzbou podľa očakávania?* Cieľom tejto práce je poskytnúť prostriedky na rýchle zodpovedanie tejto otázky definovaním metodík na extrakciu dôležitých parametrov TFB a urýchľovača s použitím výlučne samotného systému TFB a len s pozorovateľných veličín dostupných v systéme TFB.

Výskum sa zaoberal vývojom robustných techník spracovania signálu a analytických algoritmov na vytvorenie komplexného teoretického rámca, podporovaného experimentálnymi údajmi, ktorý presne vyhodnotí výkon a okamžitý stav TFB. Cieľom bolo vyvinúť praktické metódy, ktoré umožňujú meranie parametrov TFB v reálnom čase počas prevádzky urýchľovača bez ohrozenia, alebo degradácie vlastností obiehajúceho zväzku.

Tradičné techniky extrakcie parametrov spätnej väzby sa často spoliehajú na externé prístroje, sú časovo náročné, málo presné a ohrozujú stabilitu zväzku. Naproti tomu táto práca skúmala potenciál extrakcie parametrov spätnej väzby a optimalizácie výkonu TFB prostredníctvom aktívnej manipulácie s lúčom iba s použitím systému TFB. Štúdia skúmala rôzne faktory, ktoré ovplyvňujú výkon TFB, vrátane zosilnenia uzavretej spätnoväzobnej slučky, fázy spätnej väzby, oneskorenia a šumu spracovania, a navrhla metódy na kvantifikáciu týchto parametrov s cieľom zlepšiť overovanie výkonu TFB v reálnom čase.

Výskum ďalej skúmal extrakciu kľúčových parametrov urýchľovača, ako je parameter "tune" pre každý jednotlivý zhluk častíc a čas tlmenia z pozorovateľných veličín v systéme TFB. Tento prístup rieši prevádzkové problémy a zároveň prispieva k hlbšiemu pochopeniu vplyvu TFB na celkový výkon urýchľovača.

Nasledujúce časti rozoberajú dôsledky týchto zistení a zdôrazňujú ich význam pre oddelenie prevádzky a ďalší vývoj systémov TFB v urýchľovačoch častíc.

Kľúčové poznatky

Práca vytvorila niekoľko dôležitých poznatkov o technikách spracovania signálu pre systémy s transversálnou spätnou väzbou (TFB) v hadrónových urýchľovačoch. Pokroky dosiahnuté v tomto výskume sú zhrnuté nižšie a rozdelené do jednotlivých zistení, ktoré zlepšujú overovanie a optimalizáciu výkonu TFB:

Poznatok #1: *Zjednodušený model zväzku v z -rovine umožňuje aplikáciu metód číslicového spracovania signálu v problémoch dynamiky zväzkov v urýchľovačoch častíc.*

Výskum ukázal, že vývoj zjednodušeného modelu zväzku v z -rovine predstavuje významný pokrok v aplikácii metód číslicového spracovania signálu v tejto oblasti. Tento model zjednodušuje analýzu problémov dynamiky zväzku pre prístrojové aplikácie a rozširuje použiteľnosť sofistikovaných techník spracovania signálu, čím uľahčuje overovanie výkonu systémov TFB v reálnom čase.

Poznatok #2: *Analytický model senzora umožňuje praktickú implementáciu realistického správania sa LHC TFB v programoch sledovania častíc (particle tracking codes).*

Tento výskum demonštruje významný význam vývoja analytického modelu systému transversálnej spätnej väzby, ktorý opisuje vzťah medzi polohou priečnej spätnej väzby a generovaným výstupom. Umožňuje realistickú implementáciu správania priečnej spätnej väzby LHC a SPS v kódach sledovania častíc. To je kľúčové pre skúmanie stability zväzku a zabezpečenie zhlukov častíc s nízkou emitanciou v experimentoch s fyzikou vysokých energií.

Poznatok #3: *Analytické modelovanie senzora a aktuátora potvrdilo ich schopnosť spracovávať zhluky častíc jednotlivo a nezávisle.*

Tento výskum demonštruje, že dôkladná analýza systému merania polohy zväzku a aktuátora poskytuje dôležité poznatky o ich vlastnostiach a prenosových funkciách. Hardvérová implementácia preukázala schopnosť spracovávať zhluky častíc nezávisle od seba, čím minimalizuje medzysymbolovú interferenciu a zabezpečuje presné meranie a riadenie jednotlivých obiehajúcich zhlukov.

Poznatok #4: *Nové metódy rekonštrukcie súradníc priečneho fázového priestoru v reálnom čase pre jednotlivé zhluky častíc.*

Tento výskum demonštruje pokroky v chápaní a aplikácii fázových úprav pri spracovaní signálu polohy zväzku. Navrhované interpretácie priestorových a časových fázových posunov vytvárajú robustný rámec pre konverziu signálov polohy zväzku na súradnice priečného fázového priestoru, čím umožňujú efektívne monitorovanie stavu zväzku a TFB samotného v reálnom čase.

Poznatok #5: *Definícia nových metód spracovania signálu na meranie kľúčových parametrov systému priečnej spätnej väzby.*

Tento výskum demonštruje vývoj komplexnej metódy na extrakciu parametrov systému priečnej spätnej väzby, čím napĺňa potrebu praktických meracích techník v prevádzke urýchľovača. Využitím krátkych priečných vybušení s dĺžkou presne 1 obeh, generovaných kickerom systému priečnej spätnej väzby je možné monitorovanie jeho stavu a úpravy parametrov v reálnom čase.

Poznatok #6: *Pokročilé techniky spracovania signálu na extrakciu dôležitých parametrov urýchľovača.*

Tento výskum zaviedol inovatívne metódy na extrakciu dôležitých parametrov urýchľovača z pozorovateľných údajov v rámci systému priečnej spätnej väzby TFB. Schopnosť merať parameter "tune" a časovú konštantu tlmenia priečných kmitov v reálnom čase, zhluk po zhluhu, výrazne zlepšuje a rozširuje prevádzkové schopnosti a prispieva k hlbšiemu pochopeniu vplyvu TFB na výkon urýchľovača.

Poznatok #7: *Metódy rekonštrukcie priečného fázového priestoru vyžadujú pomer signálu k šumu (SNR) aspoň 30 dB na rozlíšenie zmeny Q lepšej ako 10^{-3} .*

Tento výskum demonštruje, že manažment šumu je kritický pre presné merania a overenie výkonu v reálnom čase, pretože účinnosť metód rekonštrukcie priečného fázového priestoru sa v prostredí s vysokým šumom dramaticky znižuje.

Poznatok #8: *Vysoko výkonný počítačový systém ADTObsBox pre podporu spracovania údajov v reálnom čase a výpočtovo náročných analýz.*

Tento výskum demonštruje potrebu implementácie efektívnych algoritmov, ktoré môžu fungovať v prostrediach spracovania v reálnom čase, aby sa zlepšilo overovanie výkonu TFB. Pre spracovanie dátových tokov až 20 Gb/s v reálnom čase sú potrebné vysoko výkonné servery a optimalizované algoritmy.

Poznatok #9: *Vplyv krátkych priečnych excitácií na kvalitu zväzku je zanedbateľný, ak je prítomný silný systém priečnej spätnej väzby.*

Tento výskum na základe numerických simulácií demonštruje žiadny, alebo len minimálny nárast priečnej emitácie zväzku v dôsledku vybudenia pre potreby merania ak je aktívna silná spätná väzba. To umožňuje vykonávať rutinné merania bez vytvárania strát, alebo ohrozenia kvality zväzku.

Interpretácia zistení a dôležitosť získaných výsledkov

Výsledky tejto práce predstavujú významný príspevok k pochopeniu vlastností a výkonu systémov priečnej spätnej väzby v urýchľovačoch častíc. Zdôrazňujú metodologické pokroky aj ich praktické dôsledky pre zlepšenie prevádzky urýchľovača v reálnych prostrediach.

Kľúčovým prínosom je zavedenie zjednodušeného modelu zväzku v z -rovine. Tento model umožňuje aplikáciu metód digitálneho spracovania signálu do oblasti dynamiky zväzku v urýchľovačoch a uľahčuje prístup k pokročilým technikám na overovanie výkonu systémov TFB v reálnom čase. Efektívnejšou analýzou dynamiky zväzku uľahčuje používanie sofistikovaných nástrojov z oblasti riadenia a regulácie sústav.

Ďalší dôležitý poznatok pochádza z vývoja analytického modelu pre správanie sa systému priečnej spätnej väzby LHC a SPS. Tento model umožňuje realistické implementácie systému v kódach sledovania častíc, ktoré sú kľúčové pre štúdium stability zväzku a udržiavanie zhlukov s nízkou emitanciou. Schopnosť senzora a akčného člena spracovávať zhluky nezávisle a s minimálnym šumom zabezpečuje presné meranie a riadenie, čo je kľúčová požiadavka pre urýchľovače častíc.

Navrhnuté nové metódy rekonštrukcie súradníc priečneho fázového priestoru v reálnom čase poskytujú okamžitý pohľad na správanie lúča. To umožňuje operátorom robiť informované rozhodnutia pre optimalizáciu prevádzkových parametrov a zmiernenie potenciálnych nestabilít, čím sa výrazne zvyšuje prevádzková účinnosť urýchľovačov častíc.

Významným prínosom tejto práce je zavedenie konceptu transversálnej aktivity zväzku, novej metriky, ktorá meria okamžitú amplitúdu oscilácie zväzku. Táto veličina nielen uľahčuje odvodenie rýchlosti tlmenia a zisku slučky TFB z transversálnej aktivity, ale tiež poskytuje okamžitú diagnostiku transversálnych nestabilít. Tieto nestability môžu významne ovplyvniť výkon a bezpečnosť prevádzky urýchľovača, vďaka čomu je táto diagnostická schopnosť obzvlášť cenná.

Na základe toho sme zaviedli metódu na výpočet fázového posunu TFB medzi kickerom a snímačom po jedinom transversálnom impulze. Táto metóda umožňuje okamžitú a nedeštruktívnu

analýzu fázových nastavení TFB, čo je kľúčové pre monitorovanie v reálnom čase a optimalizáciu transversálnych spätných väzieb v prostredí urýchľovača.

Okrem toho sme predstavili novú techniku na meranie časového oneskorenia kickera pomocou údajov výhradne z merania TFB. Použitím modulovaných údajov o impulze v kvadratúre sme vytvorili IQ-stopu prechádzajúcich zväzkov, čo umožňuje extrakciu časového oneskorenia. Naše zistenia demonštrujú presné merania oneskorenia TFB s presnosťou na zlomok nanosekundy. Táto úroveň presnosti je nevyhnutná pre jemné doladenie systémov TFB a zabezpečenie optimálneho výkonu.

Okrem toho, schopnosť merať parameter tune a časovú konštantu tlmenia oscilácií v reálnom čase na báze jednotlivých zhlukov z interných signálov TFB predstavuje významný pokrok v technológii urýchľovacích systémov. Táto granularita umožňuje podrobnejšie pochopenie okamžitých parametrov urýchľovača a môže viesť k zlepšeniu stability prostredníctvom adaptívnych riadiacich mechanizmov.

Obzvlášť dôležité sú poznatky o požiadavkách na pomer signálu k šumu pre zachytenie amplitúdy priečných kmitov. Požiadavka minimálneho SNR 30 dB na výpočet parametra tune s rozlíšením lepším ako 10^{-3} podčiarkuje dôležitosť riadenia šumu vo všetkých systémoch merania a diagnostiky zväzku. Tieto zistenia sú kľúčové pre vývoj budúcich meracích systémov a zdôrazňujú potrebu robustných techník spracovania signálu, ktoré fungujú efektívne aj v náročných prostrediach.

Záver, že krátke vybudenie priečných oscilácií zväzku v prítomnosti silného stabilizačného systému TFB má zanedbateľný vplyv na kvalitu zväzku naznačuje, že rutinné merania je možné vykonávať bez ohrozenia jeho kvality. Toto zistenie umožňuje integráciu pravidelných meraní TFB do prevádzkových procedúr a umožňuje proaktívne monitorovanie výkonu TFB.

S použitím nových techník predstavených v tejto práci trvá kompletná sada meraní na charakterizáciu systému TFB v LHC v CERN-e, pozostávajúca zo 16 snímačov a 8 jednotiek pre spracovanie signálu, menej ako minútu. Navrhované techniky nám umožňujú nielen skrátiť čas uvedenia TFB do prevádzky z niekoľkých zmien na menej ako minútu, ale teraz je možné vykonávať aj pravidelné, plne automatizované kontroly systému TFB v prípade podozrenia na neoptimálny výkon, čím sa ušetrí značné množstvo drahocenného strojového času.

Záver

Táto práca zaviedla množstvo nových techník a metód do oblasti systémov priečnej spätnej väzby v urýchľovačoch častíc, najmä v kontexte hadrónových urýchľovačov. Vývojom inovatívnych techník spracovania signálu a analytických modelov sme zlepšili pochopenie a aplikáciu systémov priečnej spätnej väzby. Výskum sa zaoberal kritickými otázkami týkajúcimi sa ich výkonu a funkčnosti, čím pripravil cestu pre lepšiu prevádzku urýchľovača. Mnohé z týchto techník sú už implementované v urýchľovačoch v CERN a rutinne sa používajú v jeho prevádzke. Stabilný zväzok a optimálne fungujúca priečna spätná väzba sú najlepším dôkazom toho, že prezentované techniky a nové prístupy sú spoľahlivé a veľmi hodnotné pre urýchľovače.

Jedným z najdôležitejších zistení tejto štúdie je zavedenie zjednodušeného modelu zväzku v z -rovine, ktorý uľahčuje aplikáciu metód digitálneho spracovania signálu v oblasti dynamiky zväzkov. Tento pokrok nielen zjednodušuje analýzu správania sa zväzku, ale tiež zlepšuje integráciu sofistikovaných techník do systémov analýzy dát v reálnom čase, čím sa zvyšuje prevádzková efektívnosť.

Okrem toho, vývoj analytického modelu senzora umožnil realistickú implementáciu správania priečnej spätnej väzby v kódach sledovania častíc (particle tracking), čo je nevyhnutné pre skúmanie stability zväzku v experimentoch fyziky vysokých energií. Schopnosť nezávisle spracovať zhluky, ako potvrdilo naše analytické modelovanie senzorov a akčných členov, podčiarkuje robustnosť systému TFB v LHC a jeho optimalizačný potenciál.

Nové metódy rekonštrukcie priečných fázovo-priestorových súradníc v reálnom čase predstavujú významný pokrok v prevádzkových schopnostiach. Umožnením okamžitej diagnostiky aktuálneho stavu a návrhu potrebných korekcií umožňujú tieto metódy operátorom zvýšiť výkon a efektívne minimalizovať nestability zväzku.

Komplexný prístup k meraniu kľúčových parametrov spätnej väzby a dôležitých parametrov urýchľovača otvára nové možnosti pre výskum a prevádzkové vylepšenia. Výsledky naznačujú, že monitorovanie v reálnom čase a adaptívne riadiace mechanizmy je možné implementovať na optimalizáciu výkonu urýchľovača, čím sa zabezpečí stabilita a efektívna prevádzka. Práca sa zameriava na nájdenie jednoduchého, dobre definovaného parametra alebo metódy, ktorá poskytuje jasné

odpovede na často kladené prevádzkové otázky, ako napríklad: *Funguje TFB?* Výskum prezentovaný v tejto práci prispieva vývojom metód, ktoré poskytujú rýchlu a kvalifikovanú odpoveď: *Áno, TFB funguje správne a jeho parametre sú optimálne.* Tieto praktické poznatky sú kľúčové pre oddelenie prevádzky, pretože operátorom umožňujú robiť informované rozhodnutia, zabezpečujú optimálny výkon a minimalizujú nesmierne drahý čas nečinnosti urýchľovača.

Tento výskum sa zaoberal nielen prevádzkovými aspektmi systémov TFB, ale prispel aj k hlbšiemu pochopeniu ich vplyvu na výkon urýchľovača. Prezentované metódy a poznatky kladú základ pre budúci pokrok v technológii TFB a jej aplikáciách v urýchľovačoch častíc. Budúci výskum by sa mal zamerať na širšiu použiteľnosť vyvinutých modelov a techník v rôznych prostrediach urýchľovačov. Skúmanie integrácie týchto metód do existujúcich systémov spätnej väzby, ako aj preskúmanie ich potenciálu pre úpravy v reálnom čase, bude kľúčové pre ďalší rozvoj tejto výskumnej oblasti. Ďalším zdokonaľovaním a rozširovaním týchto poznatkov môžeme ďalej zlepšiť výkon a spoľahlivosť urýchľovačov častíc a v konečnom dôsledku prispieť k pokroku vo výskume fyziky vysokých energií.

Všetky výskumné ciele tejto dizertačnej práce boli splnené.

Author's publications journals

PhD. candidate is the main author. Reference [1] was accepted by Physical Review Accelerators and Beams on 25.9.2025 and it was being processed by the journal editors at the time of writing this Dissertation abstract. Reference [1] is Q2 in Scopus, references [2] and [3] are Q3 in Scopus.

- [1] [G. Kotzian](#), X. Buffat, J. Komppula, V. Stopjakova, and D. Valuch, "Modern signal processing techniques for efficient transverse feedback systems operation in hadron accelerators," *Phys. Rev. Accel. Beams*, pp. –, Sep 2025.
- [2] [G. Kotzian](#), M. Söderén, P. Solvang, D. Valuch, and V. Stopjakova, "Reconstruction of transverse phase space from transverse feedback data for real time extraction of vital lhc machine parameters," *Journal of Physics: Conference Series*, vol. 2420, p. 012077, 01 2023.
- [3] [G. Kotzian](#), "Possibilities for transverse feedback phase adjustment by means of digital filters," *Journal of Physics: Conference Series*, vol. 874, p. 012089, 07 2017.

Author's publications proceedings

Author has 31 documents registered in Scopus database with total of 89 citations. Out of those, 33 are citations with auto-citations of all authors excluded.

The work was elaborated at European Organization for Nuclear Research (CERN) in Geneva, Switzerland. Publication habits and standards may vary across universities and institutes. In the Accelerator and Technology Sector at CERN, the publication standards include (but not limited to) the following rules:

- The co-author list comprises only individuals who have made a genuine contribution to the published work; people who have not contributed are not listed.
- Percentage contributions of individual authors are not determined.
- Prior to publication, each journal article or conference paper is thoroughly reviewed and approved at several levels of hierarchy (typically by the section leader, group leader, and in many cases also the department head).

- [1] M. Carlà, H. Bartosik, M. Beck, L. Carver, V. Kain, [G. Kotzian](#), K. Li, G. Rumolo, and C. Zannini, "Transverse Beam Dynamics Studies With High Intensity LHC Beams in the SPS," in *Proc. IPAC'19*, pp. 1062–1065, JACoW Publishing, Geneva, Switzerland, 2019.
- [2] G. P. D. Giovanni, F. Antoniou, F. Blas, Y. Brischetto, A. Findlay, [G. Kotzian](#), B. Mikulec, and G. Sterbini, "Commissioning of a New Digital Transverse Damper System at the PSB," in *Proc. IPAC'19*, pp. 1050–1053, JACoW Publishing, Geneva, Switzerland, 2019.
- [3] A. Blas and [G. Kotzian](#), "Upgraded Transverse Feedback for the CERN PS Booster," in *Proc. HB'18*, pp. 256–259, JACoW Publishing, Geneva, Switzerland, 2018.
- [4] K. Li, H. Bartosik, M. Beck, E. R. Bjørsvik, J. E. Dusatko, J. D. Fox, W. Höfle, [G. Kotzian](#), T. Levens, C. H. Rivetta, M. Schenk, and O. Turgut, "Recent Results from the Wideband Feedback System Tests at the SPS and Future Plans," in *Proc. HB'18*, pp. 38–42, JACoW Publishing, Geneva, Switzerland, 2018.

- [5] J. D. Fox, J. Dusatko, H. Bartosik, E. Bjorsvik, W. Höfle, [G. Kotzian](#), K. Li, E. Métral, C. Rivetta, B. Salvant, O. Turgut, and U. Wehrle, “Control of Intra-Bunch Vertical Motion in the SPS with GHz Bandwidth Feedback,” in *Proc. IPAC’18*, pp. 2365–2368, JACoW Publishing, Geneva, Switzerland, 2018.
- [6] W. Höfle, J. Komppula, [G. Kotzian](#), K. S. B. Li, and D. Valuch, “Transverse Feedback System for the CERN FCC-hh Collider,” in *Proc. IPAC’18*, pp. 1997–2000, JACoW Publishing, Geneva, Switzerland, 2018.
- [7] W. Höfle, H. Bartosik, E. Bjørsvik, J. Dusatko, J. Fox, [G. Kotzian](#), T. Levens, K. Li, C. Rivetta, and O. Turgut, “Impact of a Wideband Feedback Prototype System on TMCI in the SPS,” in *Proc. IPAC’18*, pp. 1208–1211, JACoW Publishing, Geneva, Switzerland, 2018.
- [8] B. Salvant, S. Antipov, G. Arduini, N. Biancacci, X. Buffat, L. Carver, P. Collier, A. Gorzawski, W. Höfle, G. Iadarola, [G. Kotzian](#), A. Lechner, T. Levens, E. Métral, D. Mirarchi, G. Rumolo, D. Valuch, and L. Methner, “Experimental Characterisation of a Fast Instability Linked to Losses in the 16L2 Cryogenic Half-Cell in the CERN LHC,” in *Proc. IPAC’18*, pp. 3103–3106, JACoW Publishing, Geneva, Switzerland, 2018.
- [9] J. M. Jimenez, D. Amorim, S. Antipov, G. Arduini, A. Bertarelli, N. Biancacci, B. Bradu, E. Bravin, G. Bregliozzi, K. Brodzinski, R. Bruce, X. Buffat, L. Carver, P. Chiggiato, S. Claudet, P. Collier, R. Alia, M. Giovannozzi, A. Gorzawski, L. Grob, W. Höfle, E. Holzer, G. Iadarola, [G. Kotzian](#), A. Lechner, T. Levens, B. Lindstrom, T. Medvedeva, L. Methner, E. Métral, A. Milanese, D. Mirarchi, D. Perini, S. Redaelli, G. Rumolo, B. Salvant, R. Schmidt, M. Valette, D. Valuch, J. Wenninger, D. Wollmann, C. Vallgren, C. Zamantzas, and M. Zerlauth, “Observations, Analysis and Mitigation of Recurrent LHC Beam Dumps Caused by Fast Losses in Arc Half-Cell 16L2,” in *Proc. IPAC’18*, pp. 228–231, JACoW Publishing, Geneva, Switzerland, 2018.
- [10] [G. Kotzian](#), “Transverse Feedback Parameter Extraction from Excitation Data,” in *Proc. IPAC’17*, pp. 1920–1923, JACoW Publishing, Geneva, Switzerland, 2017.
- [11] [G. Kotzian](#), W. Höfle, and D. Valuch, “Sensitivity of the LHC Transverse Feedback System to Intra-Bunch Motion,” in *Proc. IPAC’17*, pp. 1916–1919, JACoW Publishing, Geneva, Switzerland, 2017.
- [12] M. Söderén, [G. Kotzian](#), M. O. Sandonis, and D. Valuch, “Online Bunch by Bunch Transverse Instability Detection in LHC,” in *Proc. IPAC’17*, pp. 397–399, JACoW Publishing, Geneva, Switzerland, 2017.

- [13] L. R. Carver, X. Buffat, A. Butterworth, W. Höfle, G. Iadarola, [G. Kotzian](#), K. Li, E. Métral, M. Ojeda-Sandonis, M. Söderén, and D. Valuch, “Usage of the Transverse Damper Observation Box for High Sampling Rate Transverse Position Data in the LHC,” in *Proc. IPAC’17*, pp. 389–392, JACoW Publishing, Geneva, Switzerland, 2017.
- [14] W. Bartmann, M. Barnes, J. Boyd, E. Carlier, A. Chmielinska, K. B. Goddard, C. Schwick, L. Stoel, D. Valuch, F. Velotti, V. Vlachodimitropoulos, and C. Wiesner, “Impact of LHC and SPS Injection Kicker Rise Times on Lhc Filling Schemes and Luminosity Reach,” in *Proc. IPAC’17*, pp. 2043–2046, JACoW Publishing, Geneva, Switzerland, 2017.
- [15] J. F. Wagner, R. Bruce, H. Garcia-Morales, W. Höfle, [G. Kotzian](#), R. Kwee-Hinzmann, A. Langner, A. Mereghetti, E. Quaranta, S. Redaelli, A. Rossi, B. Salvachua, G. Stancari, R. Tomás, G. Valentino, and D. Valuch, “First Attempts at using Active Halo Control at the LHC,” in *Proc. IPAC’16*, pp. 2486–2489, JACoW Publishing, Geneva, Switzerland, 2016.
- [16] L. R. Carver, J. Barranco, N. Biancacci, X. Buffat, W. Höfle, [G. Kotzian](#), T. Lefevre, T. Levens, E. Métral, T. Pieloni, B. Salvant, C. Tambasco, N. Wang, and M. Zobov, “Current Status of Instability Threshold Measurements in the LHC at 6.5 TeV,” in *Proc. IPAC’16*, pp. 1434–1437, JACoW Publishing, Geneva, Switzerland, 2016.
- [17] B. Goddard, E. Carlier, L. Ducimetière, [G. Kotzian](#), J. A. Uythoven, and F. M. Velotti, “SPS Injection and Beam Quality for LHC Heavy Ions With 150 ns Kicker Rise Time,” in *Proc. IPAC’16*, pp. 1360–1362, JACoW Publishing, Geneva, Switzerland, 2016.
- [18] W. Höfle, [G. Kotzian](#), and D. Valuch, “Transverse Rigid Dipole and Intra-Bunch Oscillation Detection Using the Transverse Feedback Beam Position Detection Scheme in SPS and LHC,” in *Proc. IBIC’15*, pp. 456–460, JACoW Publishing, Geneva, Switzerland, 2015.
- [19] G. Iadarola, H. Bartosik, T. Bohl, B. Goddard, [G. Kotzian](#), K. Li, L. Mether, G. Rumolo, E. Shaposhnikova, M. Schenk, and M. Taborrelli, “Detailed Studies of Beam Induced Scrubbing in the CERN-SPS,” in *Proc. IPAC’15*, pp. 3908–3910, JACoW Publishing, Geneva, Switzerland, 2015.
- [20] C. H. Rivetta, J. Cesaratto, J. Dusatko, J. D. Fox, W. Höfle, K. Li, [G. Kotzian](#), and O. Turgut, “Feedback System Design Techniques for Control of Intra-bunch Instabilities at the SPS,” in *Proc. IPAC’14*, pp. 1769–1771, JACoW Publishing, Geneva, Switzerland, 2014.
- [21] J. D. Fox, J. M. Cesaratto, S. D. Santis, J. Dusatko, W. Höfle, [G. Kotzian](#), K. Pollock, C. Rivetta, O. Turgut, and U. Wehrle, “Development of a 4 GS/s Intra-bunch Instability Control System for the SPS - Next Steps,” in *Proc. IPAC’14*, pp. 1766–1768, JACoW Publishing, Geneva, Switzerland, 2014.

- [22] G. Kotzian, W. Höfle, R. J. Steinhagen, D. Valuch, and U. Wehrle, "Evaluation of Strip-line Pick-up System for the SPS Wideband Transverse Feedback System," in *Proc. IBIC'13*, pp. 690–693, JACoW Publishing, Geneva, Switzerland, 2013.
- [23] F. Dubouchet, W. Höfle, G. Kotzian, T. E. Levens, D. Valuch, and P. Albuquerque, "Tune Measurement from Transverse Feedback Signals in LHC," in *Proc. IBIC'13*, pp. 579–582, JACoW Publishing, Geneva, Switzerland, 2013.
- [24] C. H. Rivetta, H. Bartosik, J. M. Cesaratto, J. Dusatko, J. D. Fox, W. Höfle, G. Kotzian, K. Li, M. Pivi, K. Pollock, and O. Turgut, "Control of Intrabunch Dynamics at CERN SPS Ring using 3.2 GS/s Digital Feedback Channel," in *Proc. NAPAC'13*, pp. 1430–1433, JACoW Publishing, Geneva, Switzerland, 2013.
- [25] J. M. Cesaratto, H. Bartosik, J. M. Cesaratto, J. Dusatko, W. Höfle, G. Kotzian, J. Olsen, K. Pollock, C. Rivetta, O. Turgut, and U. Wehrle, "First Results and Analysis of the Performance of a 4 GS/s Intra-bunch Vertical Feedback System at the SPS," in *Proc. IPAC'13*, pp. 3070–3072, JACoW Publishing, Geneva, Switzerland, 2013.
- [26] W. Höfle, F. Dubouchet, G. Kotzian, and D. Valuch, "Performance of the LHC Transverse Damper with Bunch Trains," in *Proc. IPAC'13*, pp. 3022–3024, JACoW Publishing, Geneva, Switzerland, 2013.
- [27] W. Höfle, G. Arduini, R. D. Maria, G. Kotzian, D. Valuch, and V. A. Lebedev, "Suppression of Emittance Growth by Excited Magnet Noise with the Transverse Damper in LHC in Simulations and Experiment," in *Proc. IPAC'11*, pp. 508–510, JACoW Publishing, Geneva, Switzerland, 2011.
- [28] W. Höfle, G. Kotzian, M. Schokker, and D. Valuch, "LHC Damper Beam Commissioning in 2010," in *Proc. IPAC'11*, pp. 505–507, JACoW Publishing, Geneva, Switzerland, 2011.
- [29] V. Zhabitsky, W. Höfle, G. Kotzian, E. Montesinos, M. Schokker, and D. Valuch, "Beam Tests of the LHC Transverse Feedback System," in *Proc. RuPAC'10*, pp. 275–279, JACoW Publishing, Geneva, Switzerland, 2010.
- [30] R. D. Maria, C. Boccard, W. Höfle, G. Kotzian, C. P. Montava, and B. Salvant, "Analysis of the Performance of the SPS Exponential Coupler Striplines using Beam Measurements and Simulation Data," in *Proc. IPAC'10*, pp. 2812–2814, JACoW Publishing, Geneva, Switzerland, 2010.
- [31] G. Kotzian, F. Caspers, R. D. Maria, S. Federmann, and W. Höfle, "Ringing in the Pulse Response of Long and Wideband Coaxial Transmission Lines due to Group Delay Dispersion," in *Proc. PAC'09*, pp. 3519–3521, JACoW Publishing, Geneva, Switzerland, 2009.

- [32] R. de Maria, J. Fox, W. Höfle, [G. Kotzian](#), G. Rumolo, B. Salvant, and U. Wehrle, “Performance of Exponential Coupler in the SPS with LHC Type Beam for Transverse Broadband Instability Analysis,” in *Proc. DIPAC’09*, pp. 83–85, JACoW Publishing, Geneva, Switzerland, 2009.
- [33] V. M. Zhabitsky, W. Höfle, and [G. Kotzian](#), “Beam stability in synchrotrons with notch and all-pass filters in the feedback loop of a transverse damper,” Tech. Rep. CERN-BE-2009-013, CERN, Geneva, Apr. 2009.
- [34] T. Linnecar, M. Angoletta, L. Arnaudon, P. Baudrenghien, T. Bohl, O. Brunner, A. Butterworth, E. Ciapala, F. Dubouchet, J. Ferreira-Bento, D. Glenat, G. Hagmann, W. Höfle, C. Julie, F. Killing, [G. Kotzian](#), D. Landre, R. Louwerse, P. Maesen, P. Martinez-Yanez, J. Molendijk, E. Montesinos, C. Nicou, J. Noirjean, G. Papotti, A. Pashnin, G. Pechaud, J. Pradier, V. Rossi, J. Sanchez-Quesada, M. Schokker, E. Shaposhnikova, R. Sorokoletev, D. Stellfeld, J. Tuckmantel, D. Valuch, U. Wehrle, and F. Weierud, “Hardware and Initial Beam Commissioning of the LHC RF Systems,” Tech. Rep. LHC-PROJECT-Report-1172, CERN, Geneva, Oct. 2008.
- [35] W. Höfle, P. Baudrenghien, [G. Kotzian](#), and V. Rossi, “Digital Signal Processing for the Multi-bunch LHC Transverse Feedback System,” in *Proc. EPAC’08*, pp. 3269–3271, JACoW Publishing, Geneva, Switzerland, 2008.
- [36] W. Höfle, P. Baudrenghien, E. V. Gorbachev, F. Killing, I. Kojevnikov, [G. Kotzian](#), N. I. Lebedev, R. Louwerse, A. A. Makarov, E. Montesinos, S. V. Rabtsun, V. Rossi, M. Schokker, E. Thepenier, D. Valuch, and V. Zhabitsky, “LHC Transverse Feedback System and its Hardware Commissioning,” in *Proc. EPAC’08*, pp. 3266–3268, JACoW Publishing, Geneva, Switzerland, 2008.
- [37] [G. Kotzian](#), W. Höfle, and E. Vogel, “LHC Transverse Feedback Damping Efficiency,” in *Proc. EPAC’08*, pp. 3632–3634, JACoW Publishing, Geneva, Switzerland, 2008.
- [38] B. Goddard, M. J. Barnes, L. Ducimetière, W. Höfle, and [G. Kotzian](#), “Emittance Growth at LHC Injection from SPS and LHC Kicker Ripple,” in *Proc. EPAC’08*, pp. 3629–3631, JACoW Publishing, Geneva, Switzerland, 2008.
- [39] V. Zhabitsky, P. Baudrenghien, E. V. Gorbachev, W. Höfle, F. Killing, I. Kojevnikov, [G. Kotzian](#), N. Lebedev, R. Louwerse, A. Makarov, E. Montesinos, N. Pilyar, S. Rabtsun, V. Rossi, M. Schokker, R. Smolkov, E. Thepenier, and D. Valuch, “LHC Transverse Feedback system: First results of commissioning,” in *Proc. RuPAC’08*, pp. 97–100, JACoW Publishing, Geneva, Switzerland, 2008.

- [40] A. Koschik, B. Goddard, W. Höfle, [G. Kotzian](#), D. K. Kramer, and T. Kramer, “Abort Gap Cleaning Using the Transverse Feedback System: Simulation and Measurements in the SPS for the LHC Beam Dump System,” in *Proc. EPAC’08*, pp. 2656–2658, JACoW Publishing, Geneva, Switzerland, 2008.

References

- [1] O. Brünning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock, eds., *LHC Design Report, Vol. 1*, ch. 5.3, p. 103. CERN Scientific Information Service, June 2004.
- [2] L. Thorndahl and A. Vaughan, "Transverse feedback for the ISR," *IEEE Transactions on Nuclear Science*, vol. 20, no. 3, pp. 807–808, 1973.
- [3] R. E. C., "Bunch-to-bunch transverse feedback for the ags," Tech. Rep. 209, Brookhaven National Laboratory, 10 1984.
- [4] C. Carter, C. Christiansen, J. Donnat, G. Gelato, M. Le Gras, H. O. Schönauer, and D. J. Williams, "The transverse feedback system for the CERN PS booster," *IEEE Trans. Nucl. Sci.*, vol. 28, pp. 2270–2272, 1981.
- [5] J. Xu, J. Claus, E. Raka, A. G. Ruggiero, and T. J. Shea, "The transverse damper system for rhic," Tech. Rep. BNL-45356; CONF-910505-237, Brookhaven National Laboratory, 1 1991.
- [6] P. Baudrenghien, E. V. Gorbachev, W. Höfle, F. Killing, I. Kojevnikov, G. Kotzian, N. I. Lebedev, R. Louwerse, A. A. Makarov, E. Montesinos, S. V. Rabtsun, V. Rossi, M. Schokker, E. Thepenier, D. Valuch, and V. Zhabitsky, "LHC Transverse Feedback System and its Hardware Commissioning," tech. rep., CERN, 2008.
- [7] K. Wille, "Calculation of a nonlinear transverse feedback system," Tech. Rep. DESY PET-79/01, DESY, 1979.
- [8] J. Rogers, M. Billing, J. Dobbins, C. Dunnam, D. Hartill, T. Holmquist, B. McDaniel, T. Pelaia, M. Pisharody, J. Sikora, and C. Strohman, "Operation of a fast digital transverse feedback system in cesr," in *Proceedings Particle Accelerator Conference*, vol. 4, pp. 2426–2428 vol.4, 1995.
- [9] J.-L. Pellegrin, "Transverse Oscillations Damping with Wide-Band Feedback on SPEAR II," in *Proc. PAC'75*, pp. 1500–1505, JACoW Publishing, Geneva, Switzerland, 1975.

- [10] J. Wang, K. Zheng, W. Li, L. Wang, Z. Liu, Y. Yang, Z. Zhou, B. Sun, Y. Cheng, L. Huang, J. Cao, D. Liu, and k. ye, "Development of transverse feedback system and instabilities suppress at hls," in *2007 IEEE Particle Accelerator Conference (PAC)*, pp. 269 – 271, 07 2007.
- [11] J. Liu, J. C. Yang, J. W. Xia, D. Y. Yin, G. D. Shen, P. Li, B. Wu, S. Ruan, H. Zhao, G. Wang, Z. Q. Dong, K. D. Wang, and L. P. Yao, "Transverse impedances and collective instabilities in a heavy ion accelerator," *Phys. Rev. Accel. Beams*, vol. 21, p. 064403, Jun 2018.
- [12] N. Mounet, *The LHC Transverse Coupled-Bunch Instability*. Phd thesis, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, March 2012. Available at <https://cds.cern.ch/record/1451296?ln=en>.
- [13] W. Höfle, G. Arduini, R. D. Maria, G. Kotzian, D. Valuch, and V. A. Lebedev, "Suppression of Emittance Growth by Excited Magnet Noise with the Transverse Damper in LHC in Simulations and Experiment," in *Proc. IPAC'11*, pp. 508–510, JACoW Publishing, Geneva, Switzerland, 2011.
- [14] V. Lebedev, V. V. Parkhomchuk, V. D. Shiltsev, and G. Stupakov, "Emittance growth due to noise and its suppression with the feedback system in large hadron colliders," *Part. Accel.*, vol. 44, pp. 147–164, 1994.
- [15] E. Keil, W. Schnell, and P. Strolin, "Feedback damping of horizontal beam transfer errors," Tech. Rep. CERN 69-27, CERN, 1969.
- [16] G. P. Jackson, "The effect of chromatic decoherence on transverse injection oscillation damping," in *Proc. Technical Workshop on Feedback Control of Multi-Bunch Instabilities in Proton Colliders at the Highest Energies and Luminosities*, 1993.
- [17] J. M. Vogt, J. C. Bergstrom, S. Hu, and V. Poucki, "Bunch Cleaning at the Canadian Light Source," in *Proc. PAC'09*, pp. 4111–4113, 2009.
- [18] A. Gamelin, "SOLEIL transverse bunch-by-bunch feedback system," in *Proceedings of I.FAST Workshop 2024 on Bunch-by-Bunch Feedback Systems and Related Beam Dynamics*, 2024.
- [19] E. Gianfelice-Wendt *et al.*, "LHC Abort Gap Cleaning Studies During Luminosity Operation," in *3rd International Particle Accelerator Conference*, 5 2012.
- [20] M. Soderen, *Online Transverse Beam Instability Detection in the LHC. High Throughput Real-Time Parallel Data Analysis*. Master thesis, Linköping University, Linköping, Sweden, November 2017. Presented 13 Nov 2017.

- [21] X. Buffat, S. Furuseth, and G. Vicentini, "Chromaticity measurement using beam transfer function in high energy synchrotrons," in *Proceedings of the ICFA ABDW on High-Intensity and High-Brightness Hadron Beams*, pp. 46–51, JACoW Publishing, Geneva, Switzerland, 2021.
- [22] S. A. Antipov, D. Amorim, N. Biancacci, X. Buffat, E. Métral, N. Mounet, A. Oeftiger, and D. Valuch, "Proof-of-principle direct measurement of landau damping strength at the large hadron collider with an antidamper," *Phys. Rev. Lett.*, vol. 126, p. 164801, Apr 2021.
- [23] S. A. Antipov, C. Accettura, D. Amorim, A. Bertarelli, N. Biancacci, R. Bruce, E. Carideo, F. Carra, J. Guardia Valenzuela, A. Mereghetti, E. Métral, S. Redaelli, B. Salvant, and D. Valuch, "Transverse beam stability with low-impedance collimators in the high-luminosity large hadron collider: Status and challenges," *Phys. Rev. Accel. Beams*, vol. 23, p. 034403, Mar 2020.
- [24] D. J. Peake, M. J. Boland, G. LeBlanc, and R. P. Rassool, "Growth/Damp Measurements and Bunch-by-Bunch Diagnostics on the Australian Synchrotron Storage Ring," in *Proc. PAC'09*, no. 23 in Particle Accelerator Conference, pp. 4105–4107, JACoW Publishing, Geneva, Switzerland, 2009.
- [25] Söderén, Martin and Valuch, Daniel, "Low latency, online processing of the high-bandwidth bunch-by-bunch observation data from the transverse feedback system in the LHC," *EPJ Web Conf.*, vol. 245, p. 01036, 2020.
- [26] P. Forck, "Beam Instrumentation and Diagnostics," in *CAS - CERN Accelerator School 2019: Introduction to Accelerator Physics*, 9 2020.
- [27] R. E. Shafer, "Beam position monitoring," *AIP Conference Proceedings*, vol. 249, pp. 601–636, 03 1992.
- [28] G. Carron, S. Myers, and L. Thorndahl, "The 50 mhz transverse feedback system in the cern isr," *IEEE Transactions on Nuclear Science*, vol. 24, no. 3, pp. 1833–1835, 1977.
- [29] R. Bossart, L. Burnod, J. Gareyte, B. de Raad, and V. Rossi, "The damper for the transverse instabilities of the sps," *IEEE Transactions on Nuclear Science*, vol. 26, no. 3, pp. 3284–3286, 1979.
- [30] C. Ankenbrandt, E. F. Higgins, and R. P. Johnson, "Suppression of transverse instabilities by fast feedback in the fermilab booster," *IEEE Transactions on Nuclear Science*, vol. 24, no. 3, pp. 1698–1700, 1977.
- [31] L. Vos, "Transverse feedback system in the CERN SPS," Tech. Rep. CERN-SL-91-40-BI, CERN, 1992.

- [32] R. Takai, T. Honda, T. Nogami, T. Obina, Y. Tanimoto, and M. Tobiyama, "A New Stripline Kicker for PF-AR Transverse Feedback Damper," in *Proc. IBIC'16*, pp. 344–347, JACoW Publishing, Geneva, Switzerland, 2016.
- [33] E. V. Gorbachev *et al.*, "LHC transverse feedback system: First results of commissioning," in *21st Russian Particle Accelerators Conference*, pp. 97–100, 9 2008.
- [34] R. Bossart, J. P. Moens, and J. Mourier, "The digital delay line of the damper," Tech. Rep. CERN-SPS-ABM-83-088-0070G, CERN, Geneva, 1983.
- [35] G. Lambert, "Un convertisseur analogique numerique 8 bit ultra rapide: (Frequence d'echantillonnage 100 MHz)," Tech. Rep. CERN-SPS-ARF-Note-GL-gw-84-15, CERN, Geneva, 1984.
- [36] R. Bossart, R. Louwerse, and J. Mourier, "The digital notch filter of the damper," Tech. Rep. CERN-SPS-ABM-Note-85-10, CERN, Geneva, 1985.
- [37] V. Zhabitsky, I. Korenev, and L. Yudin, "Transverse feedback system with digital filter," in *Proceedings of International Conference on Particle Accelerators*, pp. 2543–2545 vol.3, 1993.
- [38] J. D. Fox, "Progress on intra-bunch GHz bandwidth beam feedback and applications for future accelerators," *Beam Dynamics Newsletter*, no. 77, pp. 19–34, 2019.
- [39] S. V. Furuse, X. Buffat, J. S. Pereira-Cubillo, and D. Valuch, "Emittance growth suppression with a multibunch feedback in high-energy hadron colliders: Numerical optimization of the gain and bandwidth," *Phys. Rev. Accel. Beams*, vol. 24, p. 011003, Jan 2021.
- [40] X. Buffat, W. Herr, T. Pieloni, and D. Valuch, "Modeling of the emittance growth due to decoherence in collision at the large hadron collider," *Phys. Rev. Accel. Beams*, vol. 23, p. 021002, Feb 2020.
- [41] C. M. Ankenbrandt, E. F. Higgins, and R. P. Johnson, "Suppression of Transverse Instabilities by Fast Feedback in the Fermilab Booster," in *Proc. PAC'77*, pp. 1698–1701, JACoW Publishing, Geneva, Switzerland, 1977.
- [42] W. Ebeling, "The Transverse Feedback System in DESY," in *Proc. PAC'81*, pp. 2285–2287, JACoW Publishing, Geneva, Switzerland, 1981.
- [43] J. L. Pellegrin and J. R. Rees, "Beam excitation and damping with the transverse feedback system," *Office of Scientific & Technical Information Technical Reports*, 8 1979.

- [44] C. Carter, C. Christiansen, J. Donnat, G. Gelato, M. Le Gras, H. Schonauer, and D. J. Williams, "The transverse feedback system for the cern ps booster," *IEEE Transactions on Nuclear Science*, vol. 28, no. 3, pp. 2270–2272, 1981.
- [45] A. Blas and G. Kotzian, "Upgraded Transverse Feedback for the CERN PS Booster," in *Proc. HB'18*, pp. 256–259, JACoW Publishing, Geneva, Switzerland, 2018.
- [46] R. H. Hilden, J. H. Martin, F. E. Mills, and R. A. Winje, "Apparatus for damping axial coherent beam instabilities in a synchrotron particle accelerator.," *patent*, 4 1968.
- [47] B. Sandberg, "Logic and Control Module for the Fermilab Booster Beam Damper," in *Proc. PAC'77*, pp. 1770–1772, JACoW Publishing, Geneva, Switzerland, 1977.
- [48] E. F. Higgins, "Electronics for Damping Transverse Instabilities for the Fermilab Booster Synchrotron," in *Proc. PAC'77*, pp. 1830–1833, JACoW Publishing, Geneva, Switzerland, 1977.
- [49] R. Bossart, R. Louwerse, and J. Mourier, "The digital notch filter of the damper," tech. rep., CERN, Geneva, 1985.
- [50] G. P. D. Giovanni, F. Antoniou, F. Blas, Y. Brischetto, A. Findlay, G. Kotzian, B. Mikulec, and G. Sterbini, "Commissioning of a New Digital Transverse Damper System at the PSB," in *Proc. IPAC'19*, pp. 1050–1053, JACoW Publishing, Geneva, Switzerland, 2019.
- [51] M. Schweiger, *Digitale Signalverarbeitung für die Feedbacksysteme der Elektronenspeicher-
ringe in PETRA und HERA*. Dissertation, Universität Hamburg, 1993. Ph.D. Thesis; Dis-
sertation, Universität Hamburg, 1993.
- [52] V. Vendramini, "Traitement du signal numérique pour le système de contre réaction trans-
verse utilisant un seul pick-up avec application dans le SPS et dans le LHC.," tech. rep.,
CERN, Geneva, 2002.
- [53] P. Baudrenghien, W. Höfle, G. Kotzian, and E. Vogel, "Digital Signal Processing for the
Multi Bunch LHC Transverse Feedback System," in *Proc. 11th European Particle Acceler-
ator Conference (EPAC'08), Genoa, Italy, 23-27 June, 2008*, European Particle Accelerator
Conference, (Genoa, Italy), pp. 3269–3271, June 2008.
- [54] S. Myers, "Stabilization of the Fast Head-Tail Instability by Feedback," in *Proc. PAC'87*,
pp. 503–508, JACoW Publishing, Geneva, Switzerland, 1987.
- [55] G. Lambert, "Filtre numerique en peigne fonctionnant dans une bande totale de 50 MHz." Technical Notes - 1984.

- [56] R. Louwerse, "personal communication."
- [57] V. Rossi, "Digital Signal Processing Applications and Implementation for Accelerators: Digital Notch Filter with Programmable Delay and Betatron Phase Adjustment for the PS, SPS and LHC Transverse Dampers," tech. rep., CERN, Geneva, 2002.
- [58] H. W., "Effects of pacman bunches in the lhc," Tech. Rep. LHC-Project-Report-39 ; CERN-LHC-Project-Report-39, CERN, July 1996.
- [59] A. Ribes Metidieri and X. Buffat, "Studies of pacman effects in the hl-lhc," Tech. Rep. CERN-ACC-NOTE-2019-0037, CERN, September 2019.
- [60] V. L., "Tune and stability of high intensity bunch trains in the cern sps and lhc," Tech. Rep. LHC-Project-Report-409 ; CERN-LHC-Project-Report-409, CERN, August 2000.
- [61] I. M. Solé, H. Bartosik, V. Kain, K. Paraschou, M. Schenk, and C. Zannini, "Characterisation of Bunch-by-Bunch Tune Shift Effects in the CERN SPS," in *Proc. IPAC'22*, no. 13 in International Particle Accelerator Conference, pp. 148–151, JACoW Publishing, Geneva, Switzerland, 7 2022.
- [62] S. Poprocki, S. W. Buechele, J. A. Crittenden, K. Rowan, D. L. Rubin, and J. E. San Soucie, "Measurement and modeling of electron-cloud-induced betatron tune shifts at the cornell electron-positron storage ring test accelerator," *Phys. Rev. Accel. Beams*, vol. 22, p. 081001, Aug 2019.
- [63] M. Gasior and O. R. Jones, "High Sensitivity Tune Measurement by Direct Diode Detection," in *Proc. DIPAC'05*, JACoW Publishing, Geneva, Switzerland, 2005.
- [64] L. Grech, D. Alves, M. Gasior, S. Jackson, O. Jones, T. Levens, G. Valentino, and J. Weninger, "An Alternative Processing Algorithm for the Tune Measurement System in the LHC," in *Proc. IBIC'20*, no. 9 in International Beam Instrumentation Conference, pp. 162–165, JACoW Publishing, Geneva, Switzerland, 10 2020. <https://doi.org/10.18429/JACoW-IBIC2020-WEPP27>.
- [65] R. J. Steinhagen, M. Gasior, S. Jackson, and T. G. Lucas, "Tune system performance with/without gating." https://lhc-beam-operation-committee.web.cern.ch/minutes/Meeting51-16_10_2012/2012-10-16_LB0C_Gated_BBQ_Update.pdf.
- [66] R. Bartolini and F. Schmidt, "Sussix: A computer code for frequency analysis of non-linear betatron motion," Tech. Rep. SL/Note 98-017 (AP), CERN, June 1998.

- [67] A. Ogata, "Analysis of feedback control of transverse beam oscillation by sampled-data theory," *Nuclear Instruments and Methods in Physics Research*, vol. 222, no. 3, pp. 411–419, 1984.
- [68] A. V. Oppenheim, R. W. Schaffer, and J. R. Buck, *Discrete-Time Signal Processing*. Upper Saddle River, New Jersey: Prentice-Hall Inc., 2nd ed., 1998.
- [69] D. Valuch and P. Baudrenghien, "Beam phase measurement and transverse position measurement module for the LHC," Tech. Rep. EDMS-929563, CERN, Geneva, 2007.
- [70] D. Valuch and V. Stopjakova, "New generation of very low noise beam position measurement system for the LHC transverse feedback," *Journal of Physics: Conference Series*, vol. 2420, p. 012073, Jan 2023.
- [71] S. L. Hahn, *Hilbert Transforms in Signal Processing*, pp. 193–239. Artech House, 1st ed., 1996.
- [72] D. Valuch and V. Stopjakova, "New generation of very low noise beam position measurement system for the LHC transverse feedback," *Journal of Physics: Conference Series*, vol. 2420, p. 012073, Jan 2023.
- [73] G. Kotzian, W. Höfle, and D. Valuch, "Sensitivity of the LHC Transverse Feedback System to Intra-Bunch Motion," in *Proc. IPAC'17*, pp. 1916–1919, JACoW Publishing, Geneva, Switzerland, 2017.
- [74] W. Höfle, F. Dubouchet, G. Kotzian, and D. Valuch, "Performance of the LHC Transverse Damper with Bunch Trains," in *Proc. IPAC'13*, pp. 3022–3024, JACoW Publishing, Geneva, Switzerland, 2013.
- [75] G. Kotzian, "Transverse Feedback Parameter Extraction from Excitation Data," in *Proc. IPAC'17*, pp. 1920–1923, JACoW Publishing, Geneva, Switzerland, 2017.
- [76] G. Kotzian, "Possibilities for transverse feedback phase adjustment by means of digital filters," *Journal of Physics: Conference Series*, vol. 874, p. 012089, 07 2017.
- [77] G. Kotzian, W. Höfle, and E. Vogel, "LHC Transverse Feedback Damping Efficiency," in *Proc. 11th European Particle Accelerator Conference (EPAC'08), Genoa, Italy, 23-27 June, 2008*, European Particle Accelerator Conference, (Genoa, Italy), pp. 3632–3634, June 2008.
- [78] K. Ogata, *Modern Control Engineering*. Upper Saddle River, New Jersey: Prentice-Hall Inc., 5th ed., 2010.

- [79] D. Teytelmann, "Overview of System Specifications for Bunch by Bunch Feedback Systems," in *Proc. Particle Accelerator Conference (PAC'11)*, New York, USA, March, 2011, Particle Accelerator Conference, (New York, USA), pp. 1475–1479, March 2011.
- [80] H. Hindi, J. Fox, S. Prabhakar, L. Sapozhnikov, G. Oxoby, I. Linscott, and D. Teytelman, "A Formal Approach to the Design of Multibunch Feedback Systems: LQC Controllers," in *Proc. 4th European Particle Accelerator Conference (EPAC'94)*, London, England, June, 1994, European Particle Accelerator Conference, (London, England), pp. 1622–1624, June 1994.
- [81] C.-Y. Yao, H. Shang, A. Scaminaci, and N. D. Monte, "Application of Z-transform to Noise Response Modeling of a Bunch-by-bunch Feedback System," in *Proc. International Particle Accelerator Conference (IPAC'13)*, Shanghai, China, June, 1994, International Particle Accelerator Conference, (Shanghai, China), pp. 3058–3060, Mai 2013.
- [82] M. Tobiyama and E. Kikutani, "KEKB Bunch Feedback Systems," in *Proc. International workshop on collective effects and impedance for B-factories (CEIBA95)*, Tsukuba, Japan, 12-17 Jun 1995, (Tsukuba, Japan), pp. 470–474, Jun 1995.
- [83] R. Kohaupt, "Feedback Systems at DESY," in *Proc. European Particle Accelerator Conference (EPAC'96)*, Barcelona, Spain, June, 1994, European Particle Accelerator Conference, (Barcelona, Spain), pp. 180–181, June 1996.
- [84] V. Zhabitsky, "Transverse Feedback System with a Digital Filter and Additional Delay," in *Proc. European Particle Accelerator Conference (EPAC'96)*, Barcelona, Spain, June, 1994, European Particle Accelerator Conference, (Barcelona, Spain), pp. 1833–1836, June 1996.
- [85] M. Dehler, D. Bulfone, R. Kramert, M. Lonza, P. Pollet, and T. Schilcher, "Commissioning Results of the Multi Bunch Feedback System at SLS," in *Proc. 9th European Particle Accelerator Conference (EPAC'04)*, Lucerne, Switzerland, 5-9 July, 2004, European Particle Accelerator Conference, (Lucerne, Switzerland), pp. 2508–2510, July 2004.
- [86] T. Nakamura, S. Dat'e, K. Kobayashi, and T. Ohshima, "Transverse Bunch-by-Bunch Feedback System for the SPring-8 Storage Ring," in *Proc. 9th European Particle Accelerator Conference (EPAC'04)*, Lucerne, Switzerland, 5-9 July, 2004, European Particle Accelerator Conference, (Lucerne, Switzerland), pp. 2649–2651, July 2004.
- [87] T. Nakamura, K. Kobayashi, W. X. Cheng, T. Honda, M. Izawa, T. Obina, and M. Tadano, "Single-Loop Two-Dimensional Transverse Feedback for Photon Factory," in *Proc. 10th European Particle Accelerator Conference (EPAC'06)*, Edinburgh, England, 5-9 June, 2006, European Particle Accelerator Conference, (Edinburgh, England), pp. 3006–3008, June 2006.

- [88] D. Bulfone, M. Dehler, V. Forchi, M. Lonza, and L. Zambon, "The ELETTRA Digital Multi-Bunch Feedback Systems," in *Proc. 8th European Particle Accelerator Conference (EPAC'02), Paris, France, 3-7 June, 2002*, European Particle Accelerator Conference, (Paris, France), pp. 2061–2063, June 2002.