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A NOVEL APPROACH FOR TRANSVERSE INSTABILITY DETECTION IN THE CERN PROTON SYNCHROTRON

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Abstract

The CERN Proton Synchrotron faces increasingly demanding requirements from its user community, driven by the need for higher-intensity beams that push the machine to the limits of beam stability. Transverse instabilities, such as head-tail and transverse-mode-coupling instabilities, can arise at specific stages of the machine cycles, depending on the beam parameters. This work introduces a real-time, bunch-by-bunch transverse instability diagnostic system based on wide-band beam position monitor signals. Building on recent developments in longitudinal beam observation, the system extends the software layers to measure beam profiles in both longitudinal and transverse planes. A key feature is its ability to capture multiple time windows within a single cycle, offering a complete view of beam dynamics. Real-time analysis of the transverse beam envelope evolution is performed on the acquired data to detect and characterize performance-limiting phenomena, such as transverse instabilities. The system is fully integrated into operation, allowing simultaneous beam monitoring and optimization across multiple beam types.

INTRODUCTION

The CERN Proton Synchrotron (PS) delivers a wide variety of beams to the Super Proton Synchrotron (SPS) and several dedicated experimental areas. To meet diverse physics requirements, the machine must alternate between distinct settings to deliver beams with different energies, intensities, and time structures. The recent LHC Injectors Upgrade (LIU) project aimed to double the beam intensity at increased brightness of LHC-type beams to meet the performance goals of the High-Luminosity LHC [1]. However, as intensity increases, collective effects become the dominant performance limit [2]. These collective effects are driven by the interaction between the beam and the machine impedance.

This paper addresses measurements of transverse collective instabilities, namely the head-tail instability and the Transverse Mode Coupling Instability (TMCI) in the PS. In head–tail instabilities, transverse wakefields couple the motion of particles within the bunch, potentially leading to coherent oscillations with growing amplitude. Operational stability relies on sextupole magnets to control chromaticity and an active feedback system to damp coherent oscillations, with linear coupling correction improving transverse feedback performance. While these instabilities are theoretically well understood [2–5] and reproduced by high-fidelity simulation tools [6], their real-time identification remains a challenge. Transverse signals are measured with a wide-band beam position monitor, and analog signals are fed into a digitizer to record them in the vertical and horizontal planes.

While transverse beam diagnostics exist, they typically lack continuous, cycle-by-cycle acquisition capabilities. Recent developments in longitudinal beam observation (LBO) [7] have enabled continuous monitoring and optimization of longitudinal beam profiles across multiple time windows within the beam cycle, as well as permanent cycle-by-cycle analysis. Earlier systems, such as OASIS [8], were not designed for continuous raw data acquisition, limiting persistent monitoring and flexible cycle-by-cycle configuration of beam diagnostics.

The present work extends the LBO framework to the measurement and analysis of transverse beam signals in the PS. Originally designed for longitudinal single-channel acquisition, the approach presented here introduces multi-channel acquisition of wide-band beam position monitor signals, enabling the observation of horizontal and vertical beam motion. In addition, a dedicated real-time processing pipeline has been developed to extract transverse activity indicators on a bunch-by-bunch basis, including instability metrics and head–tail mode identification. These additions extend the LBO system, creating a more advanced beam-observation system capable of monitoring both longitudinal and transverse beam quality throughout the machine cycle.

RAW DATA ACQUISITION SYSTEM

The acquisition system is developed in the Front-End Software Architecture (FESA) [9] framework. FESA is a CERN framework for building and deploying real-time control software that interfaces directly with accelerator hardware. The raw data acquisition system design is very similar to that described in [7]. The measuring system is synchronized to each machine cycle via central timing events. The digitizer receives the analog signals from the wide-band beam position monitor and acquires profiles according to trigger signals from a trigger card. The trigger card is synchronized with the beam revolution period, provided by the radio-frequency (RF) systems. Once the acquisition is complete, the data are sent over the network to downstream clients. The start of a new cycle timing event triggers the loading of settings into the digitizer memory, after which incoming triggers initiate profile recording. Once the acquisition completes, data is retrieved from memory and post-processed.

The main difference arises from the multiple channels available from the wide-band beam position monitors (hori-

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zontal, vertical, and longitudinal signals). Each channel has independent vertical scale and offset settings. These channel settings can be configured independently through the device settings properties of the FESA class. The acquisition logic was also extended to read all three channels and perform the corresponding processing on the raw signals.

REAL-TIME DATA TREATMENT

The availability of raw profiles for each beam cycle enables systematic transverse beam analysis across a variety of operational use cases. These include detecting non-optimal operational setups, monitoring beam quality, and identifying instability signatures. The following processing chain focuses on extracting robust observables for characterizing transverse bunch activity. To support online analysis, the processing pipeline was implemented in the Unified Controls Acquisition and Processing (UCAP) [10] framework, which provides centralized processing of incoming data streams.

The analysis pipeline performs amplitude normalization of all profiles using channel vertical scale values, followed by bunch identification in the longitudinal profiles to determine left and right bounds for cropping the horizontal and vertical transverse profiles around each bunch. Each longitudinal and transverse bunch profile is then smoothed with a one-dimensional low-pass filter to suppress noise. The transverse signal is subsequently weighted by the normalized longitudinal bunch distribution, reducing contributions from low-intensity regions while preserving coherent motion in the bunch core. To mitigate sensitivity to variations in bunch intensity, the weighted transverse signal is normalized to the peak of the longitudinal profile. A calibration factor based on the beam position monitor electrode sensitivity is then applied to express the signal on an approximate displacement scale consistent with the instrument response. The resulting signal provides a stable basis for detecting transverse oscillation patterns and instability modes.

Transverse activity is extracted by considering deviations from the mean signal. A sliding window of N profiles is used to compute the average, which is subtracted from each profile, leaving only fluctuations relative to the mean. This processed profile around one bunch is called the envelope. Using this procedure, coherent structures within the bunch can be emphasized, as illustrated in Fig. 1. Figure 1 shows data at injection energy of an LHC-type beam, with the transverse feedback system disabled to let the instability develop.

The signal envelope enables the definition of generic observables for transverse beam activity. In particular, the signal envelope is used both to quantify oscillation amplitude and, for specific cases, to identify instability modes. The characterization of transverse activity is derived from the signal envelope across N profiles. For each sample x, the mean absolute value across the N envelope profiles is computed to obtain the signal shown in Fig. 2. To quantify the magnitude of the bunch activity, we define a score $A = \mu_{\text{env}} + \alpha \cdot \sigma_{\text{env}}$ where μ_{env} and σ_{env} are the mean and standard deviation of the envelope amplitudes within the bunch bounds. The activity score combines the mean envelope amplitude, which captures the global oscillation level, with its standard deviation, thereby enhancing sensitivity to localized coherent structures such as head–tail modes. The weighting factor α was empirically tuned to 4 to balance robustness to noise and sensitivity to instability growth.

For head–tail instabilities, the signal envelope is further analyzed using a peak-detection algorithm to determine the mode structure, and the head-tail instability mode number is defined as the number of detected peaks minus one. The peak-detection algorithm uses minimum height and prominence thresholds to not consider low peaks and small spikes. In addition, post-processing of the detected peaks retains only those that fall below 70% of their maximum on both sides. To avoid spurious peak detections, the peak width must be compatible with the expected spatial scale of head–tail modes, approximately equal to the bunch length divided by the number of lobes.

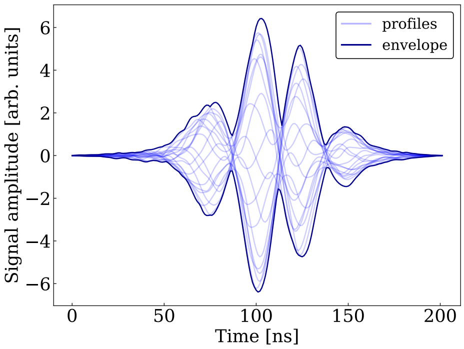


Figure 1: Transverse data processed over 20 consecutive profiles. The raw signal is cropped to isolate a single bunch, and the average signal is subtracted to emphasize deviations from the mean profile. The signal profiles exhibit four lobes, which is the signature of a head-tail mode-3.

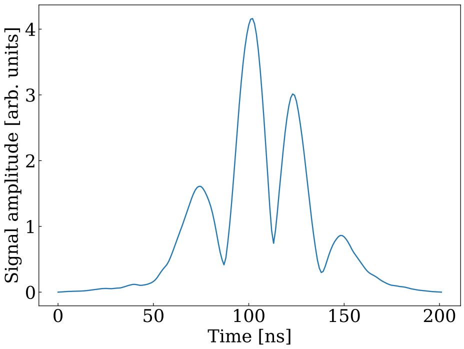


Figure 2: Signal envelope obtained from the mean absolute value across the 20 profiles shown in Fig. 1. The four lobes are clearly visible. The bunch activity and instability mode are quantified from this signal.

TRANSVERSE BEAM ACQUISITIONS

In this section, we present three operational use cases and illustrate the derived activity and mode metrics. The first arises from an incorrect setting of the injection kickers, leading to perturbed bunches. The second illustrates a strong head–tail mode-0 instability at the machine flat-top energy for an LHC-type beam. Finally, we examine a high-intensity beam during transition crossing, where a vertical instability develops once the intensity exceeds a threshold.

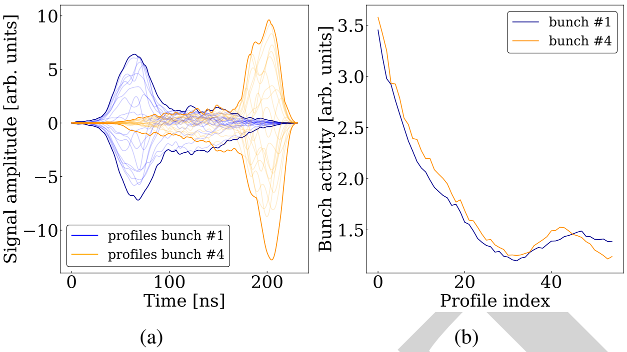
The standard LHC-type beam is composed of two injections (4 + 2 bunches) from the Proton Synchrotron Booster (PSB). During the second injection, the kicker pulse must rise and fall such that only the newly injected bunches are affected. Figure 3 shows two bunches affected in the horizontal plane by the kicker during the second injection, where the pulse timing was intentionally misaligned. As shown in Fig. 3(a), the head of the first bunch is affected when the start timing of the kicker signal is delayed. Conversely, when the timing is advanced, the tail of the fourth bunch is affected. Figure 3(b) highlights the work of the transverse damper, which counteracts these oscillations quickly to stabilize the beam.

The next example uses the same beam cycle at the machine flat-top energy (above transition). If the chromaticity is slightly negative, a strong head–tail mode-0 instability is observed. This is shown in Fig. 4, where mode-0 is clearly identifiable and leads to beam losses in the machine. The mode detection algorithm identifies a mode-0 structure.

Finally, we consider the beam for the nTOF facility [11] at nominal and increased intensity. In the PS, the transition crossing is a critical stage because the longitudinal beam dynamics change fundamentally. At this point, the phase–energy stability condition reverses, making the beam highly susceptible to collective instabilities [5]. The beam intensity was increased from 860 × 10^{10} to 920 × 10^{10} particles, and the impact on the beam after transition is shown in Fig. 5. Consecutive vertical profiles after transition show larger oscillations for the higher-intensity case in Fig. 5(a). Figure 5(b) illustrates how the activity score evolves throughout the process. The activity score is computed for both scenarios for hundreds of profiles around transition. In the nominal case, the activity score quickly returns to baseline values; in the high-intensity case, it continues to grow after the transition, providing a clear signature of beam instability.

CONCLUSION

The longitudinal beam observation framework has been extended to enable real-time monitoring of transverse beam signals using a multi-channel wide-band beam position monitor. The system performs continuous acquisition and online processing of transverse bunch profiles, from which instability indicators, such as bunch activity and head–tail mode, are derived using envelope-based analysis across consecutive profiles. Operational measurements demonstrate the system ability to identify different kinds of transverse perturbations, including injection-kicker misalignment, head–tail instabilities at flat-top energy, and instabilities during transition crossing of high-intensity bunches. The method provides a robust observable for detecting coherent transverse motion on a bunch-by-bunch basis. The framework offers a unified observation platform for both longitudinal and transverse beam dynamics in the PS, enabling continuous cycle-by-cycle monitoring and facilitating rapid identification of beam instabilities during machine operation.



(a) (b)

Figure 3: (a) Horizontal bunch signals for the 1st and 4th bunches affected by a misalignment of the injection kicker. Depending on the kicker timing, either the head of the first bunch or the tail of the fourth bunch is perturbed. (b) Bunch activity score evolution, where the transverse feedback quickly damps these oscillations and reduces the score.

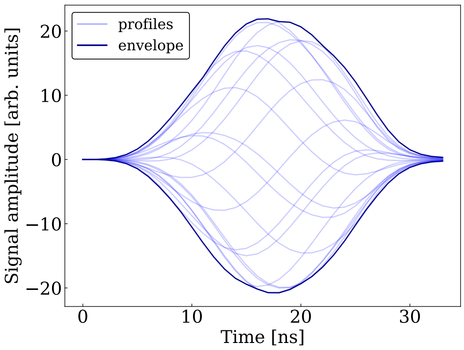
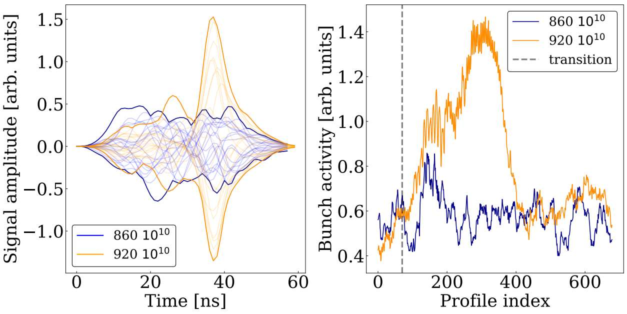


Figure 4: Strong horizontal head–tail mode-0 instability at flat-top energy of the PS for an LHC-type beam, induced by slightly negative chromaticity. The oscillation amplitude is large enough to cause beam losses.



(a) (b)

Figure 5: (a) Vertical nTOF beam signal after transition at nominal and increased intensity. (b) Bunch activity score evolution, where a clear post-transition higher activity score is observed in the high-intensity case, indicating vertical instability.

REFERENCES

[1] J. Coupard, H. Damerau, A. Funken, R. Garoby, et al, “LHC Injectors Upgrade: Technical Design Report, Volume 1: Protons”, Geneva, Switzerland, CERN-ACC-2014-0337, 2014. doi:10.17181/CERN.7NHR.6HGC

[2] E. Métral *et al.*, “Beam instabilities in hadron synchrotrons”, *IEEE Transactions on Nuclear Science*, vol. 63, no. 2, pp. 1001–1050, 2016. doi:10.1109/TNS.2015.2513752

[3] A. W. Chao, *Physics of collective beam instabilities in high energy accelerators*. New York: Wiley, 1993.

[4] E. Métral, “Intrabunch motion”, *Phys. Rev. Accel. Beams*, vol. 24, no. 1, p. 014401, 2021. doi:10.1103/PhysRevAccelBeams.24.014401

[5] S. Aumon, M. Delrieux, P. Freyermuth, et al, “Transverse Mode Coupling Instability Measurements at Transition Crossing in the CERN PS”, in *Proc. IPAC’10*, pp. 2036–2038, 2010. `http://accelconf.web.cern.ch/IPAC10/papers/TUPD049.pdf`

[6] `https://github.com/PyCOMPLETE/PyHEADTAIL`.

[7] A. Beeckman, A. Huschauer, A. Lasheen, et al, “Real-time monitoring of longitudinal beam quality across the CERN accelerator complex”, vol. 1086, p. 171244, 2026. doi:10.1016/j.nima.2025.171244

[8] S. Deghaye, D. Jacquet, I. Kozsar, et al, “OASIS: A New System to Acquire and Display the Analog Signals for LHC”, in *Proc. ICALEPCS’03*, pp. 359–361, 2003. `https://jacow.org/ica03/papers/WP502.pdf`

[9] A. Guerrero, J. J. Gras, J-L. Nougaret, et al, “CERN Front-End Software Architecture for Accelerator Controls”, in *Proc. ICALEPCS’03*, pp. 342–344, 2003. `https://jacow.org/ica03/papers/WE612.pdf`

[10] L. Cseppentő, M. Büttner, “UCAP: A Framework for Accelerator Controls Data Processing @ CERN”, in *Proc. ICALEPCS’21*, pp. 230–235, 2021. doi:10.18429/JACoW-ICALEPCS2021-MOPV039

[11] G. Tagliente, O. Aberle, et al., “The n_TOF facility at CERN”, *EPJ Web of Conferences*, vol. 297, p. 01013, 2024. doi:10.1051/epjconf/202429701013