ACTIVE METHODS OF SUPPRESSING LONGITUDINAL MULTI-BUNCH INSTABILITIES

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Abstract

Longitudinal multi-bunch instabilities limit the beam intensity and quality reach of hadron synchrotrons. In case the impedance source driving the instability is well known, for example an RF cavity, active feedback can be set up locally to reduce its effect on the beam. For multi-bunch instabilities excited by other impedances, global feedback systems are needed. A combination of both types is required to produce the high intensity beam for the future High-Luminosity LHC (HL-LHC) in the CERN Proton Synchrotron (PS). All RF cavities at 10 MHz, 20 MHz, 40 MHz and 80 MHz involved in the generation of LHC-type beams are equipped with direct, wideband feedback. To achieve an impedance reduction beyond their electrical stability limit, they are complemented by local 1-turn delay and multi-harmonic feedback systems. Additionally, a global coupled-bunch feedback loop operating in the frequency domain with a Finemet cavity as longitudinal wideband kicker damps all possible dipole oscillation modes. Beam measurements in the PS are presented, highlighting the key contributors needed to stabilize the highest intensity beams for the LHC.

INTRODUCTION

Longitudinal multi-bunch instabilities in high-intensity hadron synchrotrons are driven by the beam current inducing voltage in components of the accelerator. This voltage acts back on successive bunches, or even the same bunch after one revolution. Effort is therefore made to reduce the beam-coupling impedance as far as possible in high-intensity synchrotrons by, e.g. avoiding unnecessary cross-section changes of the beam pipe and by installing shielding or damping material in resonant structures like tanks for beam instrumentation devices. However, to improve stability beyond the feasibility of these passive impedance reduction techniques, active feedback systems are required. Additionally, some impedance sources must be kept intentionally large like accelerating cavities, to efficiently transfer energy to the beam.

Two main strategies can be applied to mitigate instabilities using feedback. In case an RF system has been identified as driving impedance source [1], a local feedback system per RF station can be deployed, which reduces the cavity impedance at the relevant frequencies. This includes the revolution harmonics at $n f_{\mathrm{rev}}$, as well as the synchrotron frequency, f_{S}, side-bands next to them at $n f_{\mathrm{rev}} \pm m f_{\mathrm{S}}$. Such feedback effectively reduces the impedance at the source, preventing instabilities from developing. However, the driving impedance source of an instability may not be known or difficult to reduce by passive and active techniques. The signature of the instability itself is then the only observable, as for example the presence of a specific component in the beam spectrum. In this case global feedback can be set up to detect that signature and to reduce it. Such feedback systems are mostly dedicated to a specific category of instabilities and can hence only cure the consequences of that particular type.

The PS at CERN is an example of an accelerator using a combination of both types of feedback to mitigate longitudinal instabilities. Within the framework of the LHC Injector Upgrade (LIU) programme the PS is prepared for its role as a pre-injector of the High-Luminosity LHC (HL-LHC), and the intensity of LHC-type multi-bunch beams will be doubled from $N_{\mathrm{b}} = 1.3 \cdot 10^{11}$ p/b to $2.6 \cdot 10^{11}$ p/b in trains of 72 bunches spaced by 25 ns [2]. Two major contributors to achieve this intensity with excellent longitudinal beam quality are presented in this contribution as examples for the two complementary approaches for mitigating longitudinal instabilities: the global coupled-bunch feedback system to suppress dipole oscillations and the local multi-harmonic feedback loops to reduce the impedance of the high-frequency cavities.

GLOBAL COUPLED-BUNCH FEEDBACK

For the production of LHC-type beams, a bunch train of 18 bunches is accelerated on harmonic $h = 21$ in the PS from a kinetic energy of $E_{\mathrm{kin}} = 1.4$ GeV to a momentum of 26 GeV/c. Three buckets remain empty as a gap for the extraction kicker. Longitudinal coupled-bunch oscillations are observed in the PS during acceleration after transition crossing and at the flat-top. An example of these oscilla-

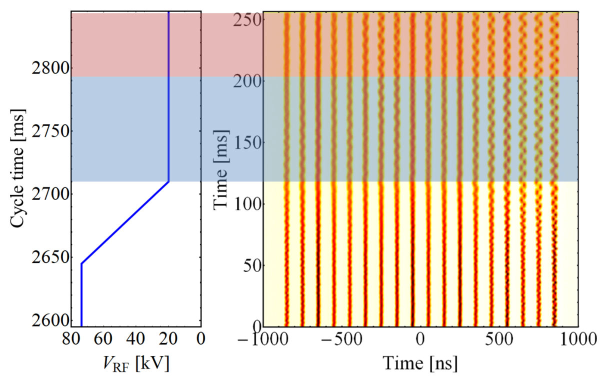

Figure 1: Dipole coupled-bunch oscillations developing at the flat-top at an intensity of about $7.2 \cdot 10^{11}$ p/b, which corresponds to $1.8 \cdot 10^{11}$ p/b at extraction after the splittings at the flat-top. The RF voltage (left) at $h = 21$ is lowered. The voltage programs for the RF systems at $h = 42$ and $h = 84$ are disabled for the measurement. The blue and red areas indicate the time periods when the two double-splittings usually take place.

tions at the flat-top is shown in Fig. 1. The dipole instability develops along the batch within 150 ms and affects particularly the bunches at the batch tail, while the first bunches are almost stable. The global coupled-bunch feedback system is an example of a damping loop suppressing the signature of the instability, independent of its driving source.

Damping of Dipole Oscillations

Damping of dipole oscillations can be achieved by detecting the phase of each bunch individually and applying a longitudinal kick to move the bunch back to its reference position in phase. While this time domain approach is common in electron accelerators operated at fixed frequency, it is less obvious to realize for hadron synchrotrons where the revolution frequency sweeps during acceleration. As an alternative approach in the frequency domain one can profit from the properties of the beam spectrum. Coupled-bunch oscillations with a phase advance of $\Delta\phi = 2\pi n/h$ from one bunch to the next, show up in the beam spectrum as an upper side-band of $n f_{\mathrm{rev}}$ and a lower side-band of $(h-n) f_{\mathrm{rev}}$, with n indicating the mode number [3]. This spectrum from 0 to $f_{\mathrm{RF}} = h f_{\mathrm{rev}}$ repeats periodically from f_{RF} to $2 f_{\mathrm{RF}}$ and above. The frequency offset with respect to the revolution frequency harmonic is an integer multiple of the synchrotron frequency, f_{S} and depends on the type of oscillation. For dipole ($m = 1$), quadrupole ($m = 2$) and higher order oscillations it appears at $n f_{\mathrm{rev}} \pm m f_{\mathrm{S}}$.

Detecting and actively removing a synchrotron frequency side-band from the beam spectrum by applying longitudinal kicks effectively results in damping the corresponding coupled-bunch oscillations [4]. This is the principle of feedback in the frequency domain. Compared to the approach in time domain, it has the advantage that a specific mode can be suppressed independently of the bunch spacing. Additionally, the feedback system is independent of the bunch arrival time and bunch pattern, as long as the phase advance from the pick-up to the longitudinal kicker is correct. This approach is therefore well suited for proton accelerators with sweeping revolution frequency.

Narrow filters are required to remove the revolution frequency harmonic from the beam spectrum, keeping only the weak synchrotron frequency side-bands nearby. The measured transfer function of one signal processing chain of the PS coupled-bunch feedback system is plotted in Fig. 2. Thanks to the symmetry of the beam spectrum, a single filter can treat two dipole coupled-bunch modes, with mode number n at $n f_{\mathrm{rev}} + f_{\mathrm{S}}$ and mode number $h-n$ at $n f_{\mathrm{rev}} - f_{\mathrm{S}}$, simultaneously.

For LHC-type beams accelerated on $h = 21$, the zero dipole oscillation mode is removed by the beam phase loop which locks the phase of the accelerating voltage to the average phase of the bunches. The remaining 20 modes with non-zero phase advance from bunch to bunch are treated by a bank of 10 parallel filters, each processing two modes as illustrated above. A wideband cavity based on Finemet material serves as a longitudinal kicker [5]. The feedback system profits from the symmetry of the beam spectrum and

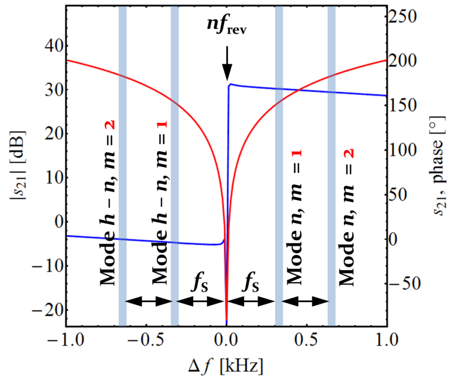

Figure 2: Transfer function in amplitude (red) and phase (blue) of one synchrotron frequency side-band filter of the PS coupled-bunch feedback system. A steep notch removes the spectral component at $n f_{\mathrm{rev}}$. The gain difference between the revolution frequency harmonic and the synchrotron frequency side-band is more than 40 dB within a frequency difference of only 300 Hz.

detects side-bands at harmonics from $f_{\mathrm{RF}}/2$ to f_{RF}, where the signals at revolution frequency harmonics are weaker and therefore easier to filter. Following a band change, the correction kicks are then applied in the base band from f_{rev} to $f_{\mathrm{RF}}/2$, where the Finemet cavity has its largest impedance.

The coupled-bunch feedback system in the PS is very efficient against dipole coupled-bunch oscillations and removes them almost entirely during acceleration and at the flat-top (Fig. 1). However, when increasing the bunch intensity beyond $7.2 \cdot 10^{11}$ p/b, corresponding to $1.8 \cdot 10^{11}$ p/b at extraction, quadrupole oscillations develop at the flat-top as illustrated in Fig. 3. The coupled-bunch mode spectrum is

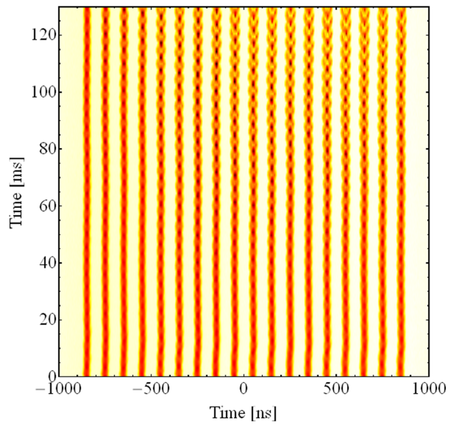

Figure 3: Measured evolution of the bunch profiles with an intensity of $7.2 \cdot 10^{11}$ p/b ($1.8 \cdot 10^{11}$ p/b at extraction after the splittings on the flat-top). Coupled-bunch feedback removes any dipole oscillations.

very similar for dipole and quadrupole oscillations, pointing to the same driving impedance source. Again, bunches at the tail of the batch are oscillating much stronger than the first few bunches after the kicker gap.

The coupled-bunch feedback system has no effect on these oscillations. Although the gain at the $\pm 2 f_S$ side-bands is even larger that at $\pm f_S$ (Fig. 2), the phase advance, adjusted to damp dipole oscillations, is not adapted. Beam tests showed that a compromise to treat dipole and quadrupole modes with the same feedback system cannot be found.

Excitation of Quadrupole Oscillations

To check the feasibility of damping the observed quadrupole coupled-bunch instabilities with the existing longitudinal kicker cavity in the PS, the excitation efficiency has been measured. Signals at the synchrotron frequency side-bands around $19 f_{rev}$ and $20 f_{rev}$ were injected to excite either dipole or quadrupole coupled-bunch oscillations. The measured relative amplitudes of the oscillations allow to estimate the maximum efficiency of an additional quadrupole damping system.

The measured mode spectrum following the excitation of a dipole oscillation is shown in Fig. 4. When moving the driving side-band from $\Delta f = f_S$ to $\Delta f = 2 f_S$, the bunch position oscillations are transformed into coupled-bunch oscillations of the bunch length. The mode spectrum (Fig. 5) is very similar to the one for the dipole oscillations. However, for the same excitation amplitude, the absolute amplitude is $2-3$ times smaller in the case of bunch length oscillations. This suggests that damping of quadrupole coupled-bunch instabilities is possible with the existing longitudinal damper cavity. However, with a damping efficiency approximately proportional to the amplitude of the excited oscillations, a reduced gain is expected for the damping of quadrupole modes compared to the one achieved with the feedback system for dipole modes.

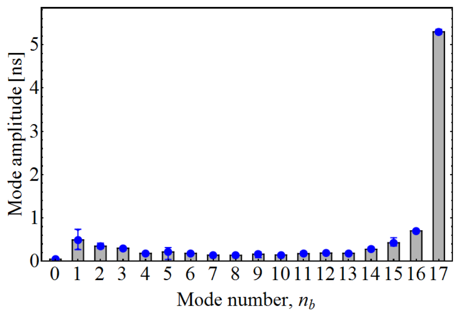

Figure 4: Measured mode spectrum at the flat-top, following an excitation at $20 f_{rev} + f_S$. The amplitude of the oscillations is measured as the maximum excursion of the bunch position with respect to the position of the stable bunches.

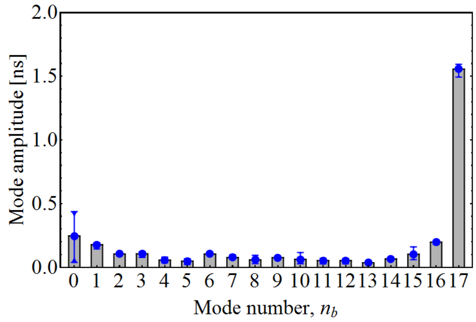

Figure 5: Measured quadrupole mode spectrum at the flat-top, following an excitation at $20 f_{rev} + 2 f_S$. The mode amplitude is defined as the maximum excursion of the bunch length oscillations.

LOCAL IMPEDANCE REDUCTION FEEDBACK

The RF cavities with their intentionally large shunt impedance require particular measures to reduce beam induced voltages.

Direct RF Feedback

Direct RF feedback is applied to most RF systems in the PS, 2.8 . . . 10 MHz [6], 20 MHz [7], 40 MHz [8] and 80 MHz [9], reducing the impedance by one to more than two orders of magnitude depending on the system. The gap voltage, containing contributions from the driving amplifier and beam induced voltage, is picked up by a probe and compared to the drive signal for the amplifier (Fig. 6, blue box). The latter does, of course, not contain any beam induced contribution. The difference, mainly corresponding to the voltage induced by the beam, is amplified and applied back to the cavity with a phase shift, effectively reducing any beam induced voltage. This technique is very efficient since it reduces the cavity impedance in the entire bandwidth of the cavity. However, due to the purely proportional gain of such systems, any phase error introduced by a loop delay limits the maximum achievable gain and bandwidth. Every effort is therefore made for direct feedback loops to reduce any delays as far as technically achievable.

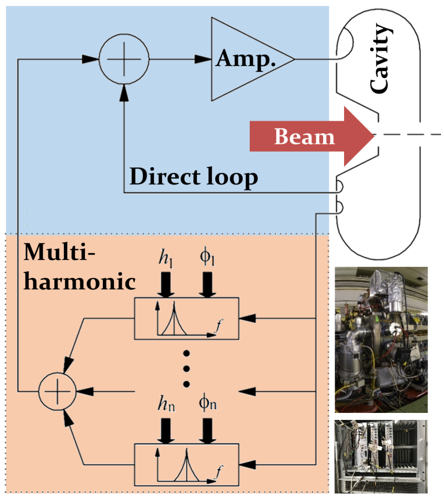

Figure 6: Simplified diagram of the local feedback systems of the 40 MHz and 80 MHz consisting of direct feedback (blue box) combined with multi-harmonic feedback (orange).

The maximum gain, G_{max}, of the direct feedback system, with no other bandwidth limitations than the cavity itself, can be written as [10]

$$\begin{aligned} G_{\mathrm{max}} &= \frac{\pi}{2} \frac{1}{R/Q} \frac{1}{\omega_{\mathrm{RF}} \tau} \\ &= \frac{\pi}{2} \cdot \frac{1}{R} \cdot \frac{1}{\Delta\omega_{-3\mathrm{dB}}} \cdot \frac{1}{\tau}, \end{aligned} \tag{1}$$

where R is the cavity impedance at resonance, $Q = \omega_{\mathrm{RF}}/\Delta\omega_{-3\mathrm{dB}}$ its quality factor and τ the overall loop delay. Although the amplifier chain is installed close to the cavity, the minimum loop delay limits the maximum gain of the direct feedback system.

Narrow-band RF Feedback

Significantly higher feedback gain can be obtained by artificially reducing the bandwidth $\Delta\omega_{-3\mathrm{dB}}$ of the feedback loop with filters. Keeping in mind that the longitudinal beam spectrum is concentrated around the revolution frequency harmonics, it is actually sufficient to reduce the cavity impedance only in these frequency ranges. A 1-turn delay feedback loop [11] uses a comb filter, a periodic system of narrow band-pass filters, centered around the revolution frequency harmonics. The width of the pass-bands then defines the maximum gain in Eq. (1) instead of the cavity bandwidth.

Even more flexibility is achieved by treating each revolution frequency harmonic within the frequency range of the RF system by an independent signal processing chain. Such a multi-harmonic feedback system has been recently implemented for the 40 MHz and 80 MHz RF systems in the PS [12]. Since these cavities are operated at fixed frequency, while the revolution frequency of the beam sweeps during acceleration, a 1-turn delay feedback loop would be difficult to realize. This is different for multi-harmonic feedback, where the gain and phase of each signal processing chain can be dynamically adjusted to perfectly match the phase of the cavity transfer function at any time during acceleration.

The measured transfer function of the prototype multi-harmonic feedback system is shown in Fig. 7. In between the revolution frequency harmonics the feedback system has little effect on the cavity impedance or may even increase it. However, at frequencies close to $n f_{\mathrm{rev}}$, where the beam current can induce voltage, deep notches in the transfer function reduce the impedance. The bandwidth of these notches must nonetheless be sufficient to cover also the first few synchrotron frequency side-bands (Fig. 8).

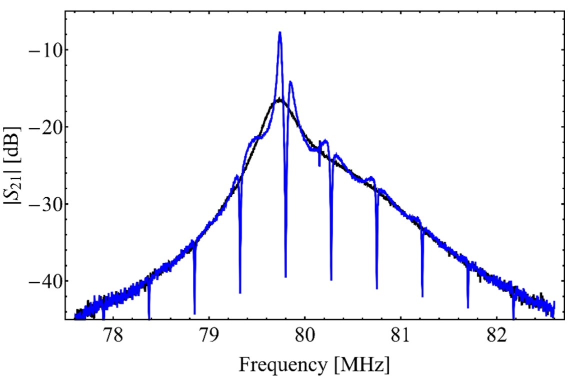

Figure 7: Measured transfer function of direct and multi-harmonic feedback loops in parallel (blue), as well as with direct feedback alone (black).

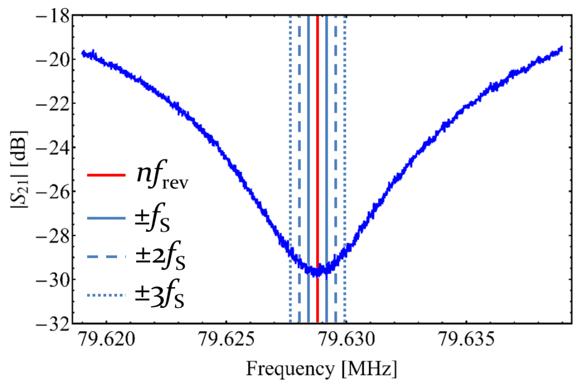

Figure 8: Transfer function measurement zoomed around one notch. The bandwidth is sufficiently large to cover the central notch and several synchrotron frequency side-bands.

To qualify the efficiency of feedback with beam, one can compare the beam induced voltage with and without the multi-harmonic feedback systems. Figure 9 illustrates the induced power in a 40 MHz cavity during the cycle for an LHC-type beam accelerated at $h = 21$ without (top) and with multi-harmonic feedback systems (bottom). The cavity is tuned to a fixed frequency corresponding to $84 f_{\mathrm{rev}}$ at the flat-top energy, where maximum voltage is required during the bunch rotation for the transfer to the SPS. The fourth harmonic of the RF frequency at $21 f_{\mathrm{rev}}$ hence sweeps into the pass-band of the 40 MHz cavity during acceleration. Before transition crossing, this spectral component is still well below the resonance frequency of the cavity, and

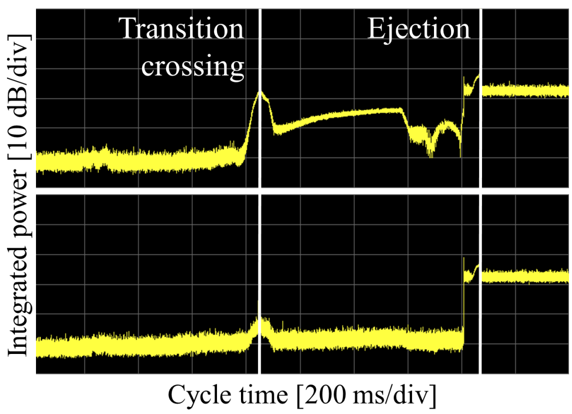

Figure 9: Beam induced power in a 40 MHz cavity without (top) and with the multi-harmonic feedback system active (bottom). With a bandwidth of ±3 MHz all revolution frequency harmonics within the bandwidth of the RF system are covered.

the bunches are yet too long to induce detectable voltage at 40 MHz. The induced voltage increases around transition crossing, as well as during the final part of acceleration to the flat-top when bunches become shorter. In this regime the feedback system efficiently counteracts the induced voltage. The observed reduction of beam induced power by up to 20 dB, corresponding to an impedance reduction by up to one order of magnitude, validates the impedance reduction expected from the transfer function measurement.

The beneficial effect of the impedance reduction on the longitudinal beam quality thanks to the multi-harmonic feedback systems can be directly observed by measuring the longitudinal emittance along the batch of 18 bunches at the arrival on the flat-top. At the HL-LHC intensity of $1.04 \cdot 10^{12}$ p/b, an uncontrolled longitudinal emittance blow-up is measured for the bunches at the tail of the batch (Fig. 10, blue) without the multi-harmonic feedback systems active

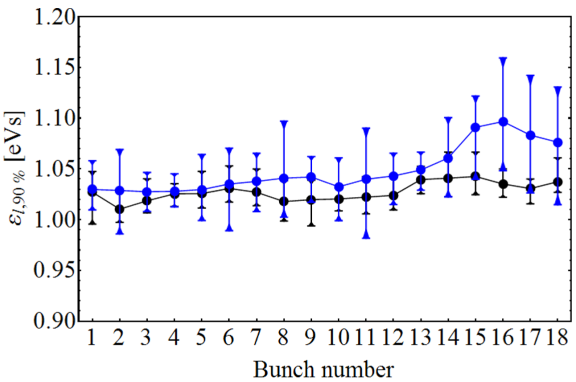

Figure 10: Longitudinal emittance along the batch without (blue) and with multi-harmonic feedback active (black) around both 80 MHz cavities at an intensity of $1.04 \cdot 10^{12}$ p/b, corresponding to $2.6 \cdot 10^{11}$ p/b at extraction. The emittance is evaluated based on bunch-by-bunch tomographic reconstruction [13] of the longitudinal distributions.

around the 80 MHz cavities. These cavities, only needed during the final bunch rotation before extraction, are equipped with a mechanical short-circuit to shield them entirely from the beam. Although it has been shown that their impedance is indeed responsible for the emittance blow-up, the mechanical short-circuit can only be used for dedicated machine development studies as the cavity cannot be pulsed for the bunch rotation under these conditions.

Activating the multi-harmonic feedback loops removes the uncontrolled emittance blow-up along the batch almost entirely (Fig. 10, black), equally well as shielding the cavity impedance with the mechanical short circuit. In the case of the 80 MHz cavities in the PS, the combination of direct and multi-harmonic feedback hence proved to reduce the impedance at the revolution frequency harmonics sufficiently well to make them transparent to the beam.

CONCLUSIONS

Active feedback systems to suppress longitudinal multi-bunch instabilities make an important contribution to preserve good longitudinal beam quality at highest intensities. In case of known impedance sources, like RF cavities, local feedback can deliver an impedance reduction well beyond the capabilities of passive techniques, in particular without requiring excessive additional RF power. Wherever possible direct feedback should be applied first. It is very robust and provides the first layer of impedance reduction. To push the feedback gain at the revolution frequency harmonics well beyond the stability limit of direct feedback, narrow-band filter feedback is applied. They may be based on comb filters, periodic with the revolution frequency, in sequence with a delay line to apply the correction on the next turn, as for the 2.8 . . . 10 MHz cavities in the PS. Multi-harmonic feedback systems like the ones implemented for the high frequency cavities in the PS provide more flexibility and gain margin. They treat the revolution frequency harmonics individually in terms of gain and phase, matching them perfectly to the impedance source they are reducing. Thanks to this flexibility, multi-harmonic feedback systems can achieve significantly higher gain than 1-turn delay feedback systems based on periodic filters.

When the source of a longitudinal instability cannot be attributed to a single driving impedance, the signature of the instability must be detected globally and compensated for by dedicated feedback to stabilize the beam instead. This path has been chosen with the frequency-domain coupled-bunch feedback system in the PS. Independent of their origin, it detects synchrotron frequency side-bands of revolution frequency harmonics as a signature of longitudinal coupled-bunch instability and actively removes them from the beam spectrum, rendering the beam stable again.

A combination of local and global feedback is used in most high-intensity accelerators to mitigate longitudinal instabilities. In the PS more than 30 feedback systems acting together (Tab. 1) allowed in 2018 to deliver LHC-type beams with an intensity of $N_\mathrm{b} = 2.6 \cdot 10^{11}$ p/b required for HL-LHC at the PS extraction. Figure 11 shows the bunch profiles during the last turn, together with practically constant bunch length along the batch of 72 bunches spaced by 25 ns.

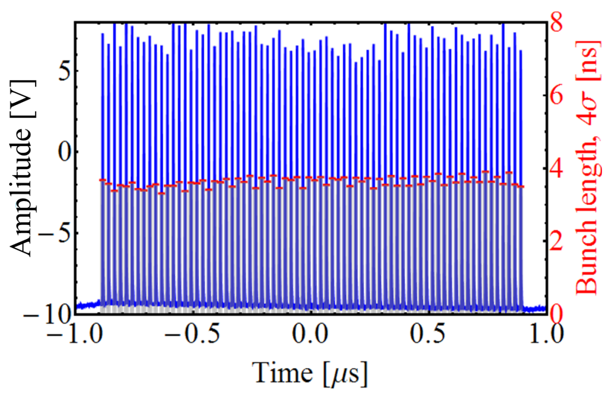

Figure 11: Beam profile (blue) and bunch length (red, 4σ Gaussian fit) during the last turn of an LHC-type beam with a bunch intensity of $2.6 \cdot 10^{11}$ p/b.

Table 1: Summary of RF feedback systems in the CERN PS

Feedback type	**Remarks**	**RF system, f_{res}**			
		2.8 . . . 10 MHz	20 MHz	40 MHz	80 MHz
Direct (18×)	• Delivers base impedance reduction • Reduction of transient beam loading • Impossible to operate without	✓ [6]	✓ [7]	✓ [8]	✓ [9]
1-turn delay (11×)	• Reduction of transient beam loading • Little effect on coupled-bunch instabilities	✓ [11]			
Multi-harmonic (7×)	• Flexible to dynamically adapt to cavity impedance • Larger gain than 1-turn delay feedback		(✓) [12]	(✓) [12]	(✓) [12]
Coupled-bunch (1×)	• Controls dipole coupled-bunch oscillations • Studying extension to quadrupole mode damping	Dedicated Finemet cavity as longitudinal wideband kicker [4, 5, 14]			

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REFERENCES

[1] A. Lasheen *et al.*, “Identification of Impedance Sources Responsible of Longitudinal Beam Instabilities in the CERN PS”, *these proceedings*.

[2] M. Meddahi, *et al.*,“LHC Injectors Upgrade Project: Towards New Territory Beam Parameters”, IPAC19, Melbourne, Australia, 2019, p. 3385.

[3] F. Pedersen, F. Sacherer, “Theory and Performance of the Longitudinal Active Damping System for the CERN PS Booster”, PAC77, Chicago, Illinois, USA, 1977, p. 1396.

[4] H. Damerau, A. Lasheen, M. Migliorati, “Observation and Damping of Longitudinal Coupled-bunch Oscillations in the CERN PS”, CERN-2018-003-CP, ICFA Mini-Workshop on Impedances and Beam Instabilities in Particle Accelerators, Benevento, Italy, 2017, p. 33.

[5] H. Damerau, M. Paoluzzi, “Design of the PS Longitudinal Damper”, CERN-ACC-NOTE-2013-0019, CERN, Geneva, Switzerland, 2013.

[6] R. Garoby *et al.*, “RF System for High-intensity Acceleration in the CERN PS”, PAC89, Chicago, Illinois, USA, 1989, p. 135.

[7] M. Morvillo *et al.*, “The PS 13.3-20 MHz RF Systems for LHC”, PAC03, Portland, Oregon, USA, 2003, p. 1724.

[8] R. Garoby *et al.*, “The PS 40 MHz Bunching Cavity”, PAC97, Vancouver, Canada, 1997, p. 2953.

[9] E. Jensen *et al.*, “The PS 80 MHz Cavities”, EPAC98, Stockholm, Sweden, 1998, p. 1773.

[10] P. Baudrenghien, “Low-level RF - Part I: Longitudinal Dynamics and Beam-based Loops in Synchrotrons”, CAS - CERN Accelerator School: RF for Accelerators, Ebeltoft, Denmark, 2010, p. 341.

[11] A. Blas, R. Garoby, “Design and Operational Results of a "One-turn-delay Feedback" for Beam Loading Compensation of the CERN PS Ferrite Cavities”, PAC91, San Francisco, California, USA, 1991, p. 1398.

[12] F. Bertin *et al.*, “Impedance Reduction of the High-frequency Cavities in the CERN PS by Multi-harmonic Feedback”, LLRF19, Chicago, Illinois, USA, 2019, arXiv:1910.06874.

[13] S. Hancock, P. Knaus, M. Lindroos, “Tomographic Measurements of Longitudinal Phase Space Density”, EPAC98, Stockholm, Sweden, 1998, p. 1520.

[14] L. Ventura *et al.*, “Excitation of Longitudinal Coupled-bunch Oscillations with the Wide-band Cavity in the CERN PS”, IPAC16, Busan, Korea, 2016, p. 1724.