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# LONGITUDINAL COUPLED-BUNCH OSCILLATION STUDIES IN THE CERN PS

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Longitudinal coupled-bunch oscillations are an important limitation for the high-brightness beams accelerated in the CERN PS. Up to the present intensities they are suppressed by a dedicated feedback system limited to the two dominant oscillation modes. In view of the proposed installation of a wide-band feedback kicker cavity within the framework of the LHC Injectors Upgrade project (LIU), measurements have been performed with the existing damping system with the aim of dimensioning the new one. Following the excitation of well-defined oscillation modes, damping times and corresponding longitudinal kick strengths are analysed. This paper summarizes the results of the observations and gives an outlook on the expected performance with the new coupled-bunch feedback.

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*Abstract*

Longitudinal coupled-bunch oscillations are an important limitation for the high-brightness beams accelerated in the CERN PS. Up to the present intensities they are suppressed by a dedicated feedback system limited to the two dominant oscillation modes. In view of the proposed installation of a wide-band feedback kicker cavity within the framework of the LHC Injectors Upgrade project (LIU), measurements have been performed with the existing damping system with the aim of dimensioning the new one. Following the excitation of well-defined oscillation modes, damping times and corresponding longitudinal kick strengths are analysed. This paper summarizes the results of the observations and gives an outlook on the expected performance with the new coupled-bunch feedback.

## INTRODUCTION

Longitudinal coupled-bunch instabilities (CBI) are observed in the CERN PS with LHC-type beams during acceleration and on the flat-top [1]. Up to the present intensities the two dominant oscillation modes are damped by a dedicated feedback (FB) system [2], which will become insufficient for the beam parameters planned within the framework of the LIU upgrade [3] of CERN's injector chain. During the first long shutdown (LS1) a new FB will therefore be installed, covering all possible modes. It will use a new wide-band kicker cavity based on Finemet® technology [4] driven by a digital signal processing chain.

In the beam spectrum measured with a wall-current monitor (WCM95) coupled-bunch (CB) oscillations manifest themselves as synchrotron frequency, $f_\mathrm{s}$, sidebands (SBs) of the revolution frequency, $f_\mathrm{rev}$, harmonics [5]. The CB mode number, $n$, characterizes the phase advance $2\pi n/N_\mathrm{B}$ from bunch to bunch for $N_\mathrm{B}$ bunches. An intra-bunch oscillation with the mode number, $m$ ($m = 1$: rigid dipole mode, $m = 2$: quadrupole, etc.) causes SBs $mf_\mathrm{s}$ away from $nf_\mathrm{rev}$. For LHC-type beams in the PS with bunch spacings below $100\,\mathrm{ns}$, only dipole, $n = 1$ modes are important. Each mode $n$ occurs twice in the spectrum, as an upper SB of $nf_\mathrm{rev}$ and as a lower SB of $(h_\mathrm{RF} - n)f_\mathrm{rev}$, where $h_\mathrm{RF}$ is the harmonic number of the main RF system.

At an energy of about $14\,\mathrm{GeV}$ and an RF voltage of $V_\mathrm{RF} \simeq 165\,\mathrm{kV}$, the $f_\mathrm{s}$ SBs are separated by only $400\,\mathrm{Hz}$ from the $f_\mathrm{rev}$ harmonics. Direct measurements of CB oscillations in the frequency domain are therefore difficult. Bunch profiles in the time domain have instead been recorded during a few periods of $f_\mathrm{s}$. Individual fits to each bunch of each turn profile allow the motion of the dipolar bunch positions versus time to be extracted. Fitting sinusoidal functions to the motion of the bunches yields oscillation amplitudes and phases per bunch, in addition to $f_\mathrm{s}$. This can be translated to mode amplitudes and phases by applying a discrete Fourier transform [6]. It is important to point out that the mode spectra obtained by this time domain technique fully resolve lower and upper $f_\mathrm{s}$ SBs. Additionally, the analysis can also be applied in the case of missing bunches, as with LHC-type beams in the PS where 18 bunches are accelerated with $h_\mathrm{RF} = 21$.

## MODE EXCITATION

The existing FB is based on a narrow-band tracking filter [7] on selected $f_\mathrm{s}$ sidebands. To study CB oscillations at other modes in view of dimensioning the new FB, the low-level part of the existing FB has been connected to a spare accelerating cavity. As powerful longitudinal kicker (up to $20\,\mathrm{kV}$), it is tunable from $2.8\,\mathrm{MHz}$ to $10\,\mathrm{MHz}$, covering $h = 6 \ldots 21$.

Two techniques can be applied to excite CB oscillations using the FB (Fig. 7): switching the FB in anti-phase or injecting a perturbation to generate a SB at $nf_\mathrm{frev} \pm f_\mathrm{s}$. The first method has been applied to ensure correct phasing of the FB prior to each measurement. However, two modes ($h_\mathrm{RF} - n$ and $n$) corresponding to both $\pm f_\mathrm{s}$ SBs of $nf_\mathrm{RF}$ are excited in parallel. More precise measurements are performed with the second technique, since it avoids switching to anti-phase and back. Additionally, by injecting the perturbation into the I/Q signal processing chain of the tracking filter, only one distinct mode at either lower, $h_\mathrm{RF} - n$ or upper, $n$ SB can be excited.

Figure 1 shows the mode spectrum following the excitation of the upper SB at $19f_\mathrm{rev}$ ($n_\mathrm{exc} = 19$) for 21 bunches in $h_\mathrm{RF} = 21$ (full machine). As expected, the $n = 19$ mode is excited most strongly. Also visible are the CB

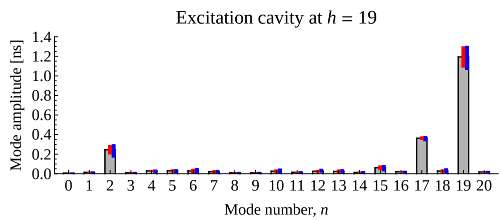


Figure 1: Example mode spectrum of 21 bunches in $h = 21$, excited at the upper SB of $19f_\mathrm{rev}$ ($E \simeq 14\,\mathrm{GeV}$, average of 5 cycles, $\pm 1\sigma$ and min-max spread are indicated by the red and blue rectangles).

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mode excited by imperfect suppression of the unwanted SB at $h_{\rm RF} - n$ and a third mode at $2n - h_{\rm RF}$. A summary of measured mode spectra for excitation harmonics of $n_{\rm exc} = 7 \ldots 20$ is illustrated in Fig. 2. In all cases the

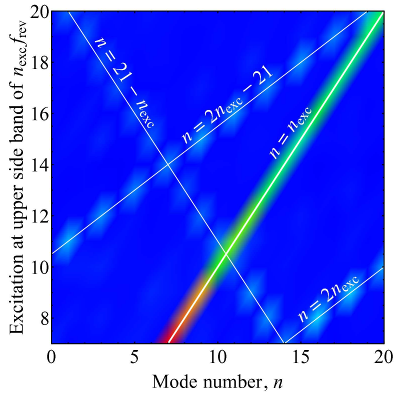


Figure 2: Mode spectra measured after excitation of the upper SB for 21 bunches at $h_{\rm RF} = 21$ (full ring).

excited mode appears most strongly ($n = n_{\rm exc}$). Additionally, the unwanted SB at $n = 21 - n_{\rm exc}$ and harmonics at $n = 2n_{\rm exc}$ or $n = 2n_{\rm exc} - 21$ are detected.

The measured mode patterns become more complicated with the operational filling pattern for LHC-type beams in the PS, where only 18 bunches are accelerated, leaving a gap of three empty buckets for extraction purposes. With only 18 bunches the CB mode number becomes $n_{\rm batch}$ and no longer corresponds directly to a harmonic of $f_{\rm rev}$: each mode $n_{\rm batch}$ generates a spectrum of $f_{\rm s}$ SBs due to the convolution with the filling pattern. However, for the relevant case of $18/21 = 6/7$ (86 %) filling, the strongest mode(s) excited are well approximated by $n_{\rm batch} = 6/7 \times n_{\rm exc}$ as indicated in Fig. 3. Again, the excitation of the unwanted SB and harmonic modes is observed.

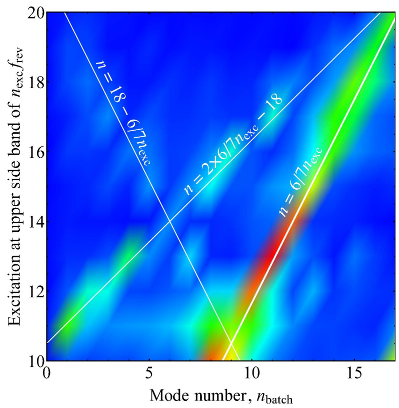


Figure 3: Mode spectra measured after excitation of the upper SB for 18 bunches at $h_{\rm RF} = 21$ (6/7 filling).

From these mode scans it becomes clear that the CB modes are only very weakly coupled to each other and that a feedback operating in the frequency domain can treat them successfully one by one.

## DAMPING RATES

The damping rates of the existing FB have been measured versus intensity, longitudinal emittance and FB gain for the most important CB modes ($n_{\rm batch} \simeq 16$, 17 corresponding to SBs at $19, 20 f_{\rm rev}$) with a beam close to the stability limit. Additionally, damping rates without FB were measured to disentangle the contribution of the FB from natural damping.

Figure 4 shows the total, $\alpha_{\rm tot}$ (red) and feedback, $\alpha_{\rm FB}$ (blue) damping rates versus FB gain, the latter were corrected by measuring the natural damping following the excitation of a stable beam. A linear increase of $\alpha$ with the

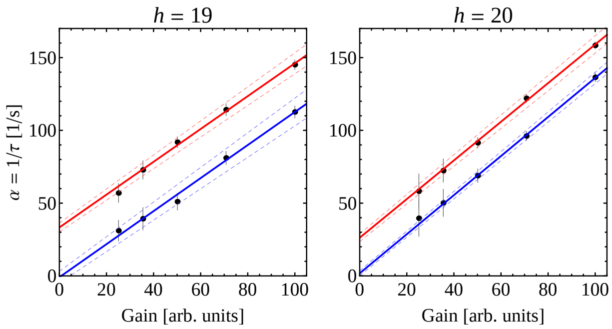


Figure 4: Damping rate versus feedback gain, uncorrected (red) and corrected for natural damping (blue).

feedback gain is observed and, for zero gain, the extrapolated $\alpha_{\rm FB}$ from a linear fit is compatible with no damping.

As the beam spectrum scales with the intensity, $N_{\rm p}$ per bunch, the $f_{\rm s}$ SB indicating a CB oscillation at constant mode amplitude is also proportional to the intensity. Hence, assuming a sufficiently strong FB kicker, the effective gain increases with intensity (Fig. 5). Natural damping

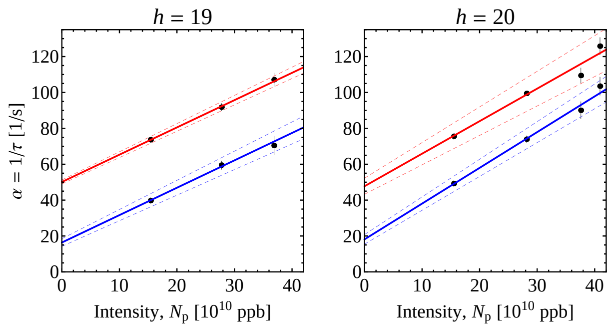


Figure 5: Damping rate versus intensity per bunch, uncorrected (red) and corrected for natural damping (blue).

was measured to be constant. Due to saturation effects in the present analogue front-end, the gain dependence on intensity may become non-linear and the fit (corrected trace, blue) does not cross the origin.

The damping rate $\alpha_{\rm FB}$ depends only weakly, if at all, on longitudinal emittance, $\varepsilon_{\rm l}$ as illustrated in Fig. 6. The spectral components at $19 f_{\rm rev}$ and $20 f_{\rm rev}$ vary by only 5 % in the relevant $\varepsilon_{\rm l}$ range, which explains the weak dependence.

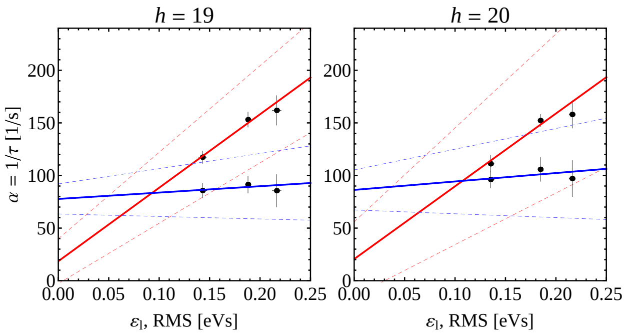


Figure 6: Damping rate versus longitudinal emittance, uncorrected (red) and corrected for natural damping (blue).

## CROSS-DAMPING

The new CB FB will be designed to cover all possible oscillation modes, hence a bandwidth of half the bunch frequency $h_{\mathrm{RF}} f_{\mathrm{rev}}/2$ is required. For the kicker cavity this can be achieved most efficiently for the range of $f_{\mathrm{rev}}$ to $10 f_{\mathrm{rev}}$ ($\simeq 0.4$–$5$ MHz). However, for the sensitive detection of the $f_s$ SBs the range from $11 f_{\mathrm{rev}}$ to $20 f_{\mathrm{rev}}$ is preferred to avoid $f_{\mathrm{rev}}$ and its first multiples.

To validate this important design choice for the new FB, the existing system has been operated with modifications to detect the upper SB of $13 f_{\mathrm{rev}}$ and correcting this oscillation at the lower SB of $8 f_{\mathrm{rev}}$ and vice versa. Growth and decay of the demodulated $f_s$ SB is illustrated in Fig. 7.

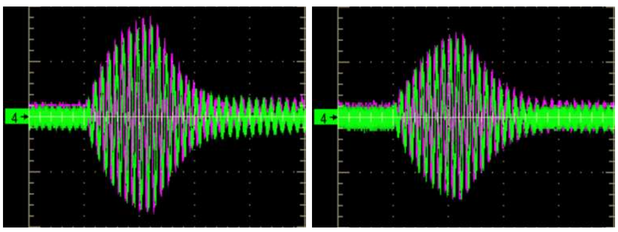

Figure 7: Excitation and damping of CB oscillations with the FB configured for cross-damping (20 ms/div), either $n = 13 \rightarrow 8$ (left) or $n = 8 \rightarrow 13$ (right).

## PERFORMANCE OF NEW FB

The main limitation of the CB FB, also after its upgrade, will be given by the maximum voltage of the kicker cavity whereas loop stability due to the large gain is less critical. The damping rate of a FB with the maximum kick strength $\Delta V_{\mathrm{FB}}$ per mode amplitude $\Delta\tau_{\mathrm{CB}}$, $g = \Delta V_{\mathrm{FB}}/\Delta\tau_{\mathrm{CB}}$ can be written [8]

$$\alpha_{\mathrm{FB}} = \frac{\eta f_{\mathrm{rev}} e_0}{4\pi f_s E \beta^2} g \ \text{ with } \ [g] = \mathrm{V/s}\,. \qquad (1)$$

To estimate the initial kick voltage as a function of the amplitude of a CB oscillation, Fig. 8 has been extracted from the voltage of the $f_s$ SB amplitude as measured with a time resolving (FFT) spectrum analyser. The required kick strength per mode amplitude is about $g \simeq 1$ kV/ns.

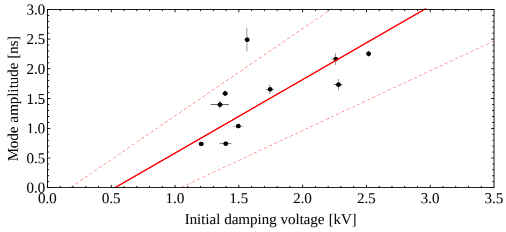


Figure 8: Initial kick voltage versus CB oscillation amplitude.

However, this assumes that the CB oscillation is already well excited, which will not be the case under operational conditions.

## CONCLUSIONS

A measurement program to study the behaviour of the present CB FB has been launched. It has shown the ability to excite single, well-defined CB oscillations and measure their damping times. The coupling between different modes is negligible and the new FB can attack each mode individually. The installation of the new FB kicker cavity is planned for the end of 2013 to start first tests with beam after LS1. An extensive simulation program has been initiated recently to benchmark the code with measurements and subsequenently to predict the feedback requirements with the increased intensities projected for LIU and finally to optimize the feedback algorithms accordingly.

## ACKNOWLEDGEMENTS

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## REFERENCES


[1] H. Damerau, S. Hancock, M. Schokker, “Longitudinal Performance with High-Density Beams for the LHC in the CERN PS,” ICFA-HB2010, Mohrschach, Switzerland, 2010, p. 193.

[2] J.-L. Vallet, “Amortissement des Instabilités Longitudinales de Modes Couplés,” unpublished presentation, 2005.

[3] R. Garoby et al., “Status and Plans for the Upgrade of the LHC Injectors,” these proceedings.

[4] M. Paoluzzi, “Beam Tests and Plans for the CERN PS Booster Wideband RF System Prototype,” these proceedings.

[5] F. Pedersen, F. Sacherer, “Theory and Performance of the Longitudinal Active Damping System,” PAC’77, Chicago, Illinois, USA, 1977, p. 1396.

[6] H. Damerau et al., “Longitudinal Coupled-bunch Instabilities in the CERN PS,” PAC’07, Albuquerque, New Mexico, USA, 2007, p. 4180.

[7] B. Kriegbaum, F. Pedersen, “Electronics for the Longitudinal Active Damping System for the CERN PS Booster,” PAC’77, Chicago, Illinois, USA, 1977, p. 1695.

[8] M. Bassetti et al., “DAΦNE Longitudinal Feedback,” EPAC’92, Berlin, Germany, 1992, p. 807.