ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAF026

HIGHER-HARMONIC RF SYSTEM FOR LANDAU DAMPING IN THE CERN PS

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Abstract

Longitudinal coupled-bunch instabilities after transition crossing and at the flat-top limit the intensity of LHC-type beams in the CERN Proton Synchrotron (PS). A dedicated coupled-bunch feedback for dipole oscillation modes, using a Finemet cavity as wide-band longitudinal kicker, suppresses the instabilities up to an intensity of about $2 \cdot 10^{11}$ particles per bunch at extraction. However, dipole and quadrupole coupled-bunch oscillations are observed beyond this intensity. At the flat-top they were damped with a 40 MHz RF cavity operated as a higher-harmonic RF system to increase Landau damping, in addition to the principal RF system at 10 MHz. The existing 40 MHz RF system, designed for RF manipulations at fixed frequency, does not cover the frequency range required during acceleration. It is therefore proposed to install a tunable RF system with a 5% relative frequency swing. This paper summarizes the observations of instability damping at the flat-top and presents preliminary parameters for the higher-harmonic RF system.

INTRODUCTION

The PS is being upgraded in the framework of the LHC Injectors Upgrade (LIU) project to increase the intensity of LHC-type beams with 25 ns bunch spacing from presently $N_b = 1.3 \cdot 10^{11}$ particles per bunch (ppb) to $2.6 \cdot 10^{11}$ ppb. The longitudinal parameters, emittance and bunch length, must not be degraded though. This implies doubling the longitudinal density of the beam and longitudinal coupled-bunch instabilities pose a major limitation to bunch intensity and quality. Without countermeasures, dipole instabilities are observed during acceleration and at the flat-top for intensities as low as $1.3 \cdot 10^{11}$ ppb. A frequency-domain coupled-bunch feedback system has therefore been installed to damp the dipole oscillations [1, 2]. It uses a wide-band Finemet cavity [3] as a longitudinal kicker to suppress synchrotron frequency side-bands at revolution frequency harmonics from f_{rev} to half the RF frequency, $f_{RF}/2$. The feedback removes dipole coupled-bunch instabilities up to an intensity of $N_b = 2 \cdot 10^{11}$ ppb, which has been regularly delivered for studies in the SPS during the 2017 run. Above this intensity dipole and quadrupole coupled-bunch instabilities are again observed. Particularly the quadrupole oscillations are not damped by the feedback designed for dipole instabilities.

As a complementary approach, longitudinal beam stability can be improved by adding RF voltage at an integer multiple of the harmonic of the fundamental RF system [4, 5]. Under appropriate conditions in terms of harmonic number and voltage ratios, as well as relative phase, the synchrotron frequency spread and consequently Landau damping are increased in a double-harmonic RF system.

In addition to its main accelerating cavities at 10 MHz ($h = 21$, LHC-type beams), the PS is equipped with RF systems at 20 MHz ($h = 42$) and 40 MHz ($h = 84$) for longitudinal manipulations of LHC-type beams at the flat-top. Although these RF systems are designed to deliver large voltage at fixed frequency in short pulses, they have been used at low voltage for studies as higher-harmonic RF systems in combination with the main RF system.

Previous measurements in the PS [6] concentrated on the RF frequency ratio of 2 (10 MHz/20 MHz), indicating a slight stability improvement when the RF voltage at the higher harmonic is applied in counter-phase to stretch the bunch (bunch lengthening mode). The recent studies focus on operating a cavity at $h = 84$ as a higher-harmonic RF system. The harmonic number ratio of 4, motivated by the experience from the SPS with its RF systems at 200 MHz and 800 MHz [7, 8], proved to be efficient to damp both, dipole and quadrupole coupled-bunch instabilities in the PS.

OBSERVATIONS AT FLAT-TOP

To observe the evolution of coupled-bunch instabilities, the RF manipulations, normally executed at flat-top energy with LHC-type beams, were deactivated, leaving sufficient time to keep 18 bunches in a single ($h = 21$) or double-harmonic RF system (10 MHz/40 MHz).

Damping of Dipole Oscillations

Figure 1 (left) illustrates the instabilities measured towards the end of the flat-top in a double-harmonic RF system at $h = 21$ and 84 with a voltage ratio of 0.25. The coupled-

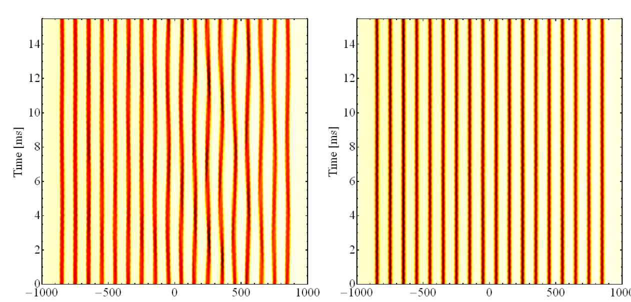

Figure 1: Comparison of dipolar coupled-bunch oscillations with 20 kV at $h = 21$ in combination with 5 kV at $h = 84$ in bunch lengthening (left) and bunch shorting (right) mode.

bunch feedback has been disabled. With the two RF systems in counter-phase (left, bunch lengthening mode) there is no beneficial effect on longitudinal stability compared to the single harmonic case. Inverting the relative phase of the higher-harmonic RF voltage (bunch shortening mode) suppresses the dipole coupled-bunch instability (Fig. 1, right).

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The corresponding coupled-bunch mode spectra [9], averaged over 10 cycles, are shown in Fig. 2. Almost all dipole

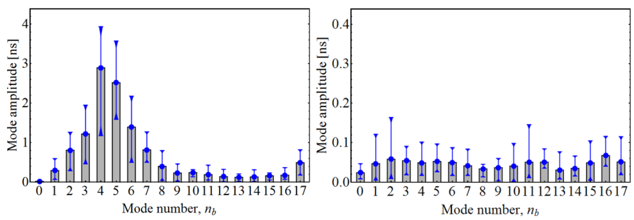

Figure 2: Dipolar coupled-bunch mode spectra for the same conditions as in the examples in Fig. 1. The blue bars indicate the total spread of the 10 cycles measured.

oscillation modes are lowered by an order of magnitude or beyond. Efficient damping has been observed down to voltage ratios of ~ 0.1. It is worth noting that the conditions in terms of harmonic number and voltage ratio are actually similar to the ones operationally used to stabilize the LHC-type beam in the SPS [8].

Damping of Quadrupole Oscillations

With the coupled-bunch feedback enabled, the dipole instabilities are removed at least up to an intensity of $N_b = 2.0 \cdot 10^{11}$ ppb at extraction. However, the feedback has no effect on the quadrupole coupled-bunch oscillations which start to occur at slightly higher intensity. Again the damping of these oscillations in a double-harmonic RF system has been studied at the flat-top.

Figure 3 (left) illustrates the evolution of the bunch profiles in the case of bunch lengthening (top) and bunch shortening (bottom) mode. Adding the higher-harmonic voltage in

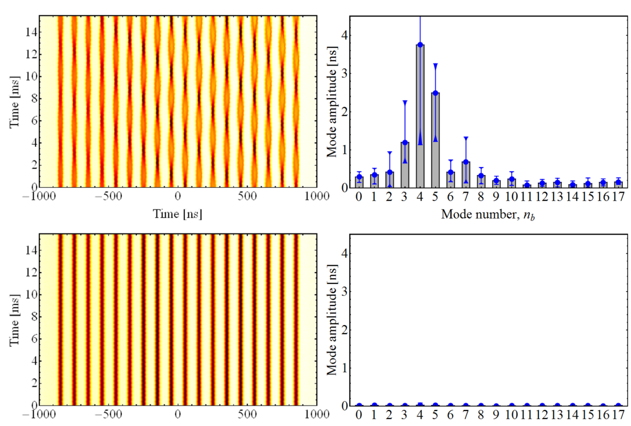

Figure 3: Quadrupole coupled-bunch oscillations in a double-harmonic RF system, 10 MHz and 40 MHz at a voltage radio of about 0.1. The relative phase of the 40 MHz RF voltage has been set to bunch lengthening (top) and bunch shortening (bottom) mode [2].

counter-phase to the main RF system has no effect on the clean quadrupole coupled-bunch instability. The average mode spectrum is shown in Fig. 3 (right). When flipping the sign of the higher-harmonic RF system the quadrupole instability is fully suppressed.

To check the dependency of the damping with respect to the relative phase between both RF systems, their relative phase has been scanned. Figure 4 summarizes the mode spectra versus the relative phase of the RF voltage at 40 MHz. All quadrupole coupled-bunch modes are damped simulta-

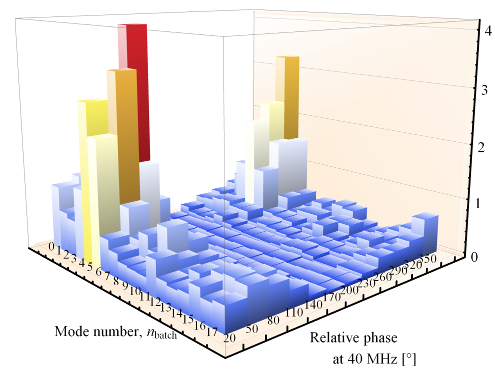

Figure 4: Measured quadrupole coupled-bunch mode spectra versus relative phase between the two RF systems. The voltage ratio is $V_2/V_1 = 0.15$.

neously and a valley of stability is found in a phase range of about ±30°, illustrating the robustness of the damping in a double-harmonic RF system.

DAMPING DURING ACCELERATION

Above bunch intensities of $N_b = 2.0 \cdot 10^{11}$ ppb at extraction dipole and quadrupole coupled-bunch instabilities are already present during acceleration. The revolution frequency of protons increases by 1.3% from transition energy, $E = 5.7$ GeV ($\gamma_{tr} = 6.1$), to the flat-top.

The existing high-frequency RF systems, in particular the ones at 40 MHz and 80 MHz, are optimized for a large RF voltage of 300 kV at fixed frequency [10, 11]. Measurements to explore the maximum frequency range of the 40 MHz system at low RF voltages in the 10 kV regime were performed, showing that these cavities can only cover of the order of 100 kHz, about five times less than the frequency range required to operate them from transition to the flat-top. Additionally, since first signs of longitudinal beam quality degradation have recently been observed at the intermediate energy of $E_{kin} = 2.5$ GeV, it is desirable to operate the higher-harmonic RF system from injection to flat-top energy.

Under the assumption that none of the existing RF systems in the PS is suitable for beam stabilization during acceleration, studies for a dedicated RF system optimized for moderate voltage in the relative frequency range of 5.3% have been launched. Such an RF system would cover the full frequency swing from the injection at 2 GeV (after the upgrade during the long shut-down 2, LS2) to extraction.

The efficiency of the instability damping is related to the increase of the relative synchrotron frequency spread within the bunch. Hence, the choice of the harmonic number with respect to the main RF system at $h = 21$ for LHC-type beams

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depends on the achievable synchrotron frequency spread. At the same time the synchrotron frequency distribution must remain monotonous within the bunch [12]. Loss of Landau damping may cause instability otherwise.

The normalized synchrotron frequencies, $\omega_s(\varepsilon_l)/\omega_{s0}$ during the acceleration from transition crossing to the arrival of the flat-top are shown in Fig. 5 for single particle emittances from the centre of the bunch up to to 2 eVs in steps of 0.2 eVs. Comparison at constant voltage ratio, $V_2/V_1 = 0.2$, has been chosen to illustrate the effect of a fixed voltage in the higher-harmonic RF system. The final longitudinal emit-

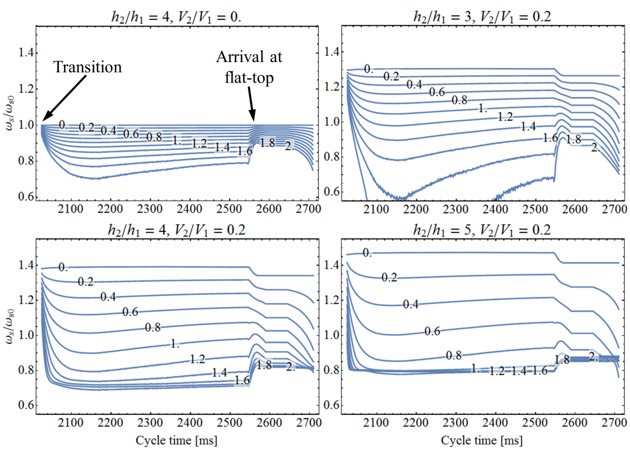

Figure 5: Single particle synchrotron frequency distributions during the acceleration for the single harmonic case (top right) and harmonic number ratios, h_2/h_1, of 3 (top right), 4 (bottom left) and 5 (bottom right).

tance per bunch at the transfer to the SPS is $\varepsilon_l = 0.35$ eVs with a bunch splitting by four at the flat-top. Hence the maximum longitudinal emittance relevant for LHC-type beams during acceleration in the PS is about $\varepsilon_l = 1.4$ eVs.

Whenever the relative synchrotron frequencies for different longitudinal emittances are well separated in Fig. 5, this indicates a parameter region with large synchrotron frequency spread, associated with large Landau damping. Synchrotron frequency spread lines close together or even overlapping indicate parameter regions with low damping or even loss of Landau damping due to $d\omega_s(\varepsilon_l)/d\varepsilon_l = 0$ for parts of the bunch distribution.

Compared to the single-harmonic case the synchrotron frequency spread approximately doubles when adding a higher-harmonic RF voltage at the third harmonic of the fundamental RF frequency (Fig. 5, top right). The synchrotron frequency spread is increased for bunches with a longitudinal emittance of more than $\varepsilon_l = 2$ eVs.

With the higher-harmonic RF system at four times the fundamental RF harmonic (Fig. 5, bottom left), the synchrotron frequency spread is about three times larger compared to the single-harmonic RF system for a bunch emittance of up to about $\varepsilon_l = 1.5$ eVs. The beneficial effect has been confirmed by the measurements at the flat-top. Further increase of the harmonic ratio results in even larger synchrotron frequency spread, but only for bunches with emittances below $\varepsilon_l = 1$ eVs. Based on these considerations, the harmonic number ratio of 4 ($h_1 = 21/h_2 = 84$) seems the most favourable compromise for stabilisation of LHC-type beams.

PRELIMINARY RF SYSTEM CONSIDERATIONS

The preliminary frequency ranges and RF voltages of a dedicated RF system for increased Landau damping at three or four times the frequency of the fundamental cavities are summarized in Table 1. For the most attractive option of

Table 1: Preliminary Parameters of the Higher-harmonic RF System for Longitudinal Damping

	$h_2/h_1 = 3$	$h_2/h_1 = 4$
Harmonic	63	84
RF Voltage [kV]	~ 60 . . . 80	~ 40 . . . 50
Ratio, V_2/V_1	0.3 . . . 0.4	0.2 . . . 0.25
Frequency [MHz]	29.65 . . . 30.04	39.53 . . . 40.05
Tuning range	1.3%	
(5.7 . . . 26 GeV)	Transition energy to flat-top	
Frequency [MHz]	28.49 . . . 30.04	37.98 . . . 40.05
Tuning range	5.3%	
(2 . . . 26 GeV)	Flat-bottom (after LS2) to flat-top	

the higher-harmonic RF system at 40 MHz ($h_2 = 84$) and a tuning range of 5.3%, the technology for ferrite-tuned cavities with similar or larger tuning range and RF voltage exists [13,14]. However, due to the limited space in the short straight section in the PS and the large aperture requirement (150 mm beam-pipe diameter), the preliminary study aims at distributing the total RF voltage over two cavity units.

Studies are also ongoing to check the interest in a higher-harmonic RF system for fixed-target beams. In this case the third harmonic ($h_2 = 63$) option may become interesting again. By extending the relative tuning range to 6.8% the cavity could also cover $h_2 = 64$, four times the main harmonic during acceleration through transition ($h_1 = 16$).

CONCLUSIONS

Dipole and quadrupole coupled-bunch instabilities limit the intensity of LHC-type beams in the PS to $N_b = 2 \cdot 10^{11}$ ppb at extraction, even with the dipole coupled-bunch feedback in place. Beam studies with existing RF systems at the flat-top demonstrate that a double RF configuration with a harmonic number ratio of 4 is capable of damping both, dipole and quadrupole oscillations. To extend this approach to the instabilities during acceleration, a new tunable RF system is proposed which sweeps with the increasing revolution frequency of the beam. In parallel further beam measurements are planned in 2018 to refine the parameters of this additional RF system.

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ACKNOWLEDGEMENTS

The authors would like to thank R. Madrak, W. A. Pellico and C. Y. Tan from Fermilab, as well as the newly formed Landau cavity study team at CERN.

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