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OBSERVATION AND DAMPING OF LONGITUDINAL COUPLED-BUNCH OSCILLATIONS IN THE CERN PS

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Abstract

Longitudinal coupled-bunch instabilities pose a major limitation to the intensity and quality of LHC-type beams in the CERN Proton Synchrotron (PS). The oscillations are excited above transition energy and mainly driven by the impedance of the main accelerating cavities at around 10 MHz. When approaching the flat-top these cavities are partly short-circuited. However, due to the sweeping revolution frequency, the spectral components of the beam move towards the resonances of the high frequency cavities at 20 MHz, 40 MHz and 80 MHz. Hence different coupled-bunch oscillation mode patterns are observed during acceleration and at the flat-top. A dedicated frequency domain damping system has been installed. While dipole coupled-bunch instabilities are well suppressed, quadrupole oscillations remain, as well as longitudinal blow-up due to the impedance of the high frequency cavities. Recent results obtained with the coupled-bunch feedback are presented together with first studies using alternative mitigation techniques for the instabilities.

INTRODUCTION

In the framework of the LHC Injectors Upgrade (LIU) project the PS is being upgraded to deliver an intensity per bunch of $N_b = 2.6 \cdot 10^{11}$ ppb for a bunch spacing of 25 ns, twice the present nominal intensity of beams delivered to the Large Hadron Collider (LHC). Longitudinal coupled-bunch instabilities, both dipole and quadrupole, occur during acceleration and at the flat-top. They limit the achievable intensity and beam quality. For the dipole coupled-bunch instabilities a prototype feedback system is available for studies since 2016. It consists of a wide-band Finemet cavity [1] operated in the frequency range from the revolution frequency, f_{rev} to half the main RF frequency, $f_{RF}/2$, and a low-level signal processing covering all possible dipole oscillation modes [2]. Although a new intensity range, beyond $N_b \simeq 1.4 \cdot 10^{11}$ ppb, has become accessible with the coupled-bunch feedback, dipole oscillations reappear above a bunch intensity of $N_b = 2.0 \cdot 10^{11}$ ppb. Additionally, quadrupole coupled-bunch instabilities are observed. Increasing the longitudinal emittance to stabilize the beam is not compatible with the tight constraints at transfer between PS and SPS.

The main harmonic of the RF system changes during the acceleration cycle. In total 6 bunches are injected into $h = 7$ and the principal RF harmonic is then brought to $h = 21$ by triple splitting [3] at a kinetic energy of 2.5 GeV [4]. Following acceleration of 18 bunches through transition to the flat-top at $h = 21$, each bunch is split in four parts by a sequence of two bunch splittings, $h = 21 \rightarrow 42 \rightarrow 84$. The coupled-bunch oscillations occur during acceleration above transition energy and at the flat-top [5], hence before the quadruple splitting prior to extraction.

Since all bunch intensities in this contribution are given with reference to bunches at extraction from the PS to the SPS, held with $h = 84$, the bunch intensity at $h = 21$ during acceleration is four times that value.

DIPOLE COUPLED-BUNCH INSTABILITIES

In the frequency domain coupled-bunch oscillations manifest as synchrotron frequency, f_s, side-bands of the revolution frequency harmonics [6], which makes them difficult to observe directly in the PS. The side-bands are only about $f_s \simeq 400$ Hz away from the strong spectral lines at multiples of f_{rev}. Additionally, the lower and upper f_s side-bands are driven by different oscillation modes. The phase motion of the bunches can be extracted from profiles measured in time domain instead. A discrete Fourier transform translates the oscillation amplitudes and phases per bunch to mode amplitude and phases [7]. The same analysis technique can also be applied to quadrupole coupled-bunch oscillations where the bunch length replaces the bunch phase.

Acceleration

Fig. 1 shows the mode spectrum of a dipole coupled-bunch instability during acceleration. The zero mode is suppressed by the beam phase loop. Low and high mode numbers are strongest, which in the spectrum appear at frequencies close to f_{RF}. They are most likely excited by the impedance of the main accelerating cavities at 10 MHz [7].

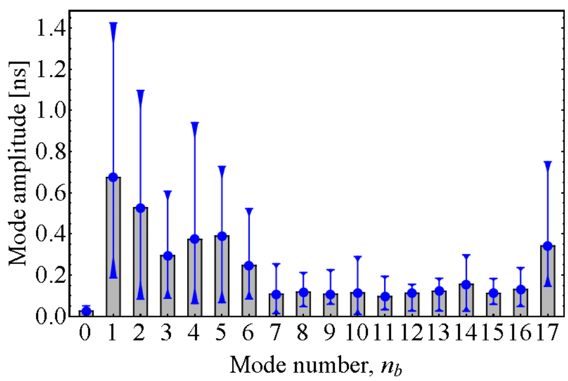

Figure 1: Mode spectrum of the dipole coupled-bunch oscillations during acceleration. The blue bars indicate the total spread of ten acceleration cycles (2011 data). The mode number, n_b, refers to modes within the batch of 18 bunches.

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Flat-top

The mode pattern changes at the flat-top, when the RF voltage is reduced in preparation of the RF manipulations and the gaps of the main cavities are sequentially short-circuited. The motion of bunches in time domain is illustrated in Fig. 2. The dipole mode spectrum (Fig. 3) at the flat-top differs significantly from the one during acceleration (Fig. 1). In addition to the modified impedance of the accelerating cavities at the flat-top, the spectral components of the beam at the 84th and 168th harmonic of f_{rev} move to the resonance frequencies of the 40 MHz and 80 MHz cavities.

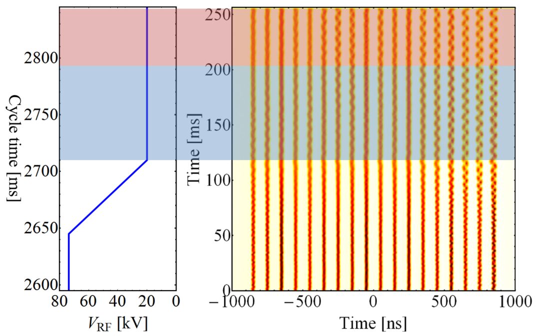

Figure 2: Dipole coupled-bunch instability at flat-top. The shaded areas indicate the time windows when the bunch splittings $h = 21 \rightarrow 42$ (blue) and $h = 21 \rightarrow 42$ (red) normally take place.

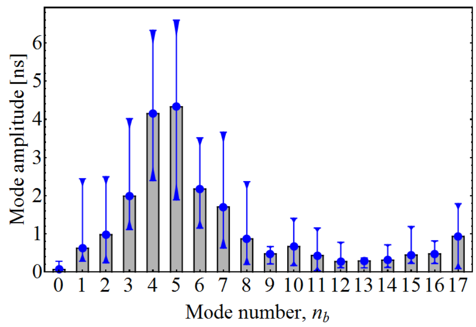

Figure 3: Mode spectrum of the dipole coupled-bunch oscillations at the end of the flat-top (Fig. 2).

COUPLED-BUNCH FEEDBACK

The coupled-bunch feedback extracts the f_s side-bands and reduces them by injecting a correction in opposite phase [6]. Out of the 21 possible dipole oscillation modes for LHC-type beams accelerated at $h = 21$, the zero mode is removed by the beam phase loop. The 20 other modes are covered by the coupled-bunch feedback as lower and upper side-bands at 10 revolution frequency harmonics. To avoid detecting the weak side-bands close to the much stronger f_{rev} harmonics at low frequencies, the band from $f_{\mathrm{RF}}/2$ to f_{RF} has been chosen. However, due to higher shunt impedance of the Finemet cavity at low frequencies, the correction signals are translated to the frequency band from f_{rev} to $f_{\mathrm{RF}}/2$ [2].

The benefit on longitudinal stability during acceleration is sketched in Fig. 4. The time domain evolution reveals a strong bunch oscillation, dipole and quadrupole, without the coupled-bunch feedback and the tomographic reconstruction illustrates the distorted bunch distribution. With the feedback system switched on the instability is fully suppressed. Although only an example measurement of one bunch is shown in Fig. 4, all bunches are reproducibly stabilized during each cycle with the feedback.

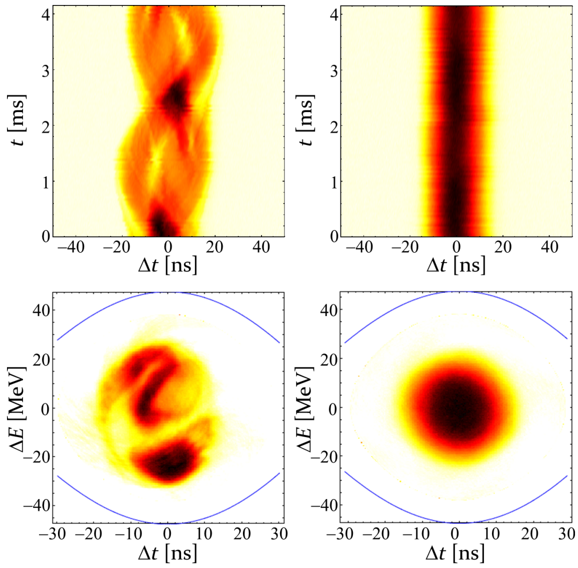

Figure 4: Instability (bunch number 12 of an 18-bunch batch) towards the end of acceleration without (left) and with (right) the coupled-bunch feedback. The intensity per bunch at extraction is $N_b = 2.0 \cdot 10^{11}$ ppb.

Thanks to the full mode coverage, stabilisation is also achieved at the flat-top, during the bunch splittings from $h = 21$ to $h = 84$ (Fig. 5). The significant beam quality improvement is again clearly visible and reproducible from cycle to cycle. However, the coupled-bunch feedback designed for dipole oscillation modes has no effect on quadrupole-type instabilities which occur in the PS when pushing the intensity beyond an equivalent intensity of $N_b = 2 \cdot 10^{11}$ ppb.

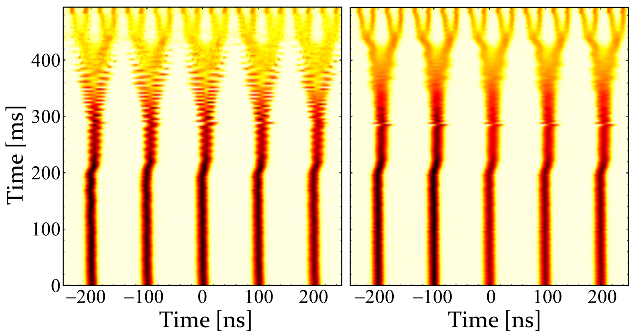

Figure 5: Bunch evolution during the flat-top splittings with the coupled-bunch feedback disabled (left) and enabled (right). The intensity per bunch at extraction is $N_b = 1.8 \cdot 10^{11}$ ppb.

QUADRUPOLE COUPLED-BUNCH OSCILLATIONS

With the feedback for dipole instabilities in place, coupled-bunch quadrupole (bunch length) oscillations are observed, again starting during acceleration after transition crossing and at the flat-top.

Acceleration

At the longitudinal emittance compatible for producing the nominal emittance $\varepsilon_l = 0.35$ eVs (matched area definition, [8]) at extraction, the quadrupole oscillations are naturally well damped (Fig. 6, left). The mode spectrum shows only small amplitudes with minor impact on beam quality. This changes when increasing the longitudinal beam

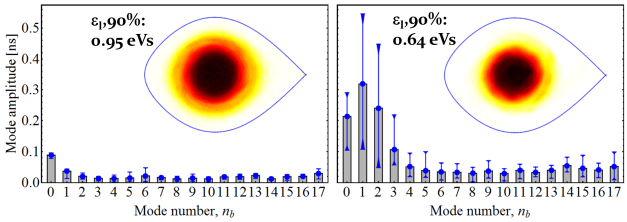

Figure 6: Mode spectrum of the quadrupole coupled-bunch instability after transition crossing for two different longitudinal emittances. The intensity per bunch at extraction is $N_b = 2.0 \cdot 10^{11}$ ppb.

density. The longitudinal emittance is reduced by about 50% by decreasing the controlled longitudinal blow-up (Fig. 6, right). The higher density appears to be above the threshold of the instability and the dominant amplitudes of the quadrupole coupled-bunch oscillations grow by almost an order of magnitude.

Flat-top

At the flat-top the dipole instabilities are again well controlled by the feedback system. It has no effect though on the quadrupole instabilities (Fig. 7) slowly developing during the time which is normally used for synchronisation and quadruple splitting. Analysing the quadrupole oscillations at the end of the flat-top reveals the mode spectrum shown in Fig. 8. As for the dipole modes (Fig. 3) the mode numbers, $n_b = 4$ and 5 are strongest, indicating that dipole and quadrupole oscillations are excited by the same impedance source.

Measurements at the flat-top confirm that the feedback has no effect on quadrupole oscillations.

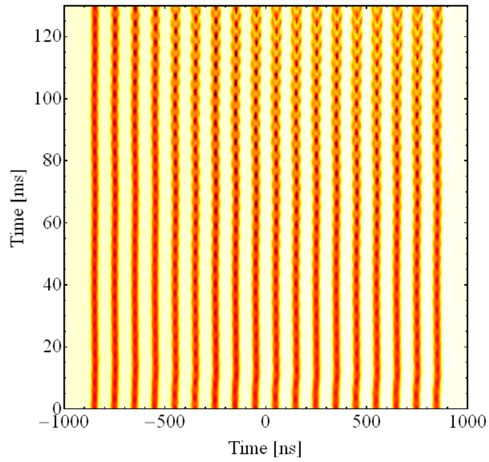

Figure 7: Mode spectrum of the quadrupole coupled-bunch instability at flat-top. The equivalent intensity per bunch at extraction is $N_b = 2.0 \cdot 10^{11}$ ppb.

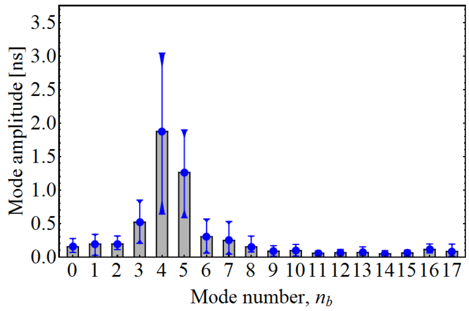

Figure 8: Mode spectrum of the quadrupole coupled-bunch oscillation at the flat-top (Fig. 7).

HIGHER HARMONIC RF SYSTEM

For the RF manipulations at the flat-top the PS is equipped with RF systems at 20 MHz, 40 MHz and 80 MHz. The 20 MHz system has been operated as a higher-harmonic RF system in the past [9], showing only a slight stability improvement when set in counter-phase with respect to the main RF system. Motivated by the experience with the double-harmonic RF configuration in the SPS [10] with a harmonic number ratio of four, recent studies concentrated on the 40 MHz RF system to increase the synchrotron frequency spread within the bunch.

At the flat-top the effect on stability of a double-harmonic RF system, 10 MHz and 40 MHz, adding some extra voltage at $h = 84$ in addition to the principal RF harmonic of $h = 21$ has been investigated. The higher-harmonic RF voltage has been applied in counter-phase (bunch lengthening mode) and in phase (bunch shortening mode).

Fig. 9 summarizes stabilisation due to the double-harmonic RF system. Applying the voltage at $h = 84$ in bunch lengthening mode has no measurable effect on the quadrupole coupled-bunch oscillations (Fig. 9, top) while switching only the phase of the 40 MHz to bunch shortening mode (Fig. 9, bottom) stabilizes the beam. Already 10% of the voltage of the main RF system is sufficient to significantly reduce the quadrupole instability.

The studies in 2017 with the double-harmonic RF system were focused on the mitigation of the quadrupole coupled-bunch oscillations in combination with the feedback suppressing the dipole modes. Preliminary tests in 2016 were nonetheless performed showing that also dipole instabilities are well damped by the double-harmonic RF system [11].

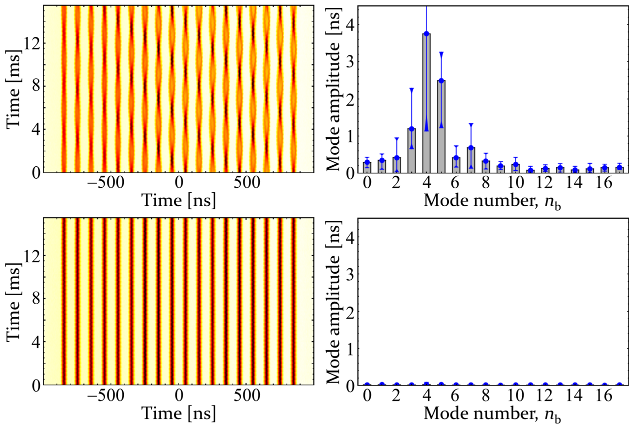

Figure 9: Quadrupole coupled-bunch oscillations in a double-harmonic RF system, 10 MHz and 40 MHz at a voltage radio of about 10%, the lowest ratio tested. The relative phase of the 40 MHz RF voltage has been set to bunch lengthening (top) and bunch shortening (bottom) mode.

The synchrotron frequency spread within the bunch is significantly increased in the presence of the higher-harmonic RF system (Fig. 10). For a bunch with the nominal longitudinal emittance of $\varepsilon_l = 4 \cdot 0.35$ eVs $= 1.4$ eVs a harmonic number ratio of four is most efficient to increase the synchrotron frequency spread within the bunch. Voltage ratios above 25% result in saddle points in the synchrotron frequency distribution detrimental for stability [10].

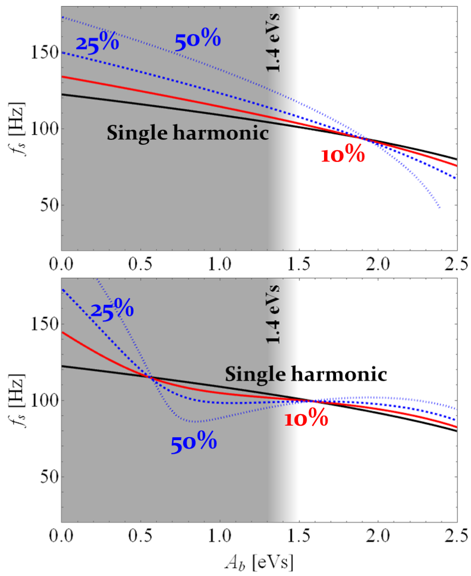

Figure 10: Synchrotron frequency distribution in the single harmonic RF system with an RF voltage of 20 kV at $h = 21$ (black) at the flat-top in the PS. In combination with voltage from a higher harmonic RF system at $h = 42$ (top) and $h = 84$ (bottom), the synchrotron frequency spread increases, depending on the voltage ratio [11].

Although longitudinal stabilisation has been demonstrated, the existing 40 MHz RF cavities are optimized for large RF voltage at fixed frequency. They can hence only be operated at or close to the flat-top and not during acceleration, when the quadrupole coupled-bunch oscillations occur first.

CONCLUSIONS

Longitudinal coupled-bunch instabilities with a reproducible mode spectrum are observed in the CERN PS. The mode pattern changes between acceleration and flat-top. The instabilities are most likely driven by the impedance of main cavities at 10 MHz. At the arrival on the flat-top the RF voltage is reduced and unused cavities are short-circuited by gap relays, hence changing their impedance and the resulting mode spectrum. With a wide-band coupled-bunch feedback in place, dipole oscillations are suppressed up to an intensity of $N_b = 2.0 \cdot 10^{11}$ ppb. Above this intensity dipole and quadrupole coupled-bunch bunch instabilities occur. The feedback, designed to cover all possible dipole modes, has no effect on the quadrupole instabilities. As a complementary approach, an existing 40 MHz RF system has been operated as a higher-harmonic RF system for beam studies. It proved very efficient in damping the quadrupole coupled-bunch instability at the flat-top. Suppressing the instability during acceleration would require a dedicated RF system, capable of sweeping with the increasing revolution frequency. Such a system is now under study.

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