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# LONGITUDINAL COUPLED-BUNCH INSTABILITY STUDIES IN THE PS

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*Abstract*

The main longitudinal limitation for LHC-type beams in the PS are coupled-bunch instabilities. A dedicated prototype feedback system using a Finemet cavity as a longitudinal kicker has been installed. Extensive tests with beam have been performed to explore the intensity reach with this feedback. The maximum intensity with nominal longitudinal emittance at PS extraction has been measured, as well as the emittance required to keep the beam longitudinally stable at the design intensity for the High-Luminosity LHC (HL-LHC). A higher-harmonic cavity is a complementary option to extend the intensity reach beyond the capabilities of the coupled-bunch feedback. Preliminary machine development (MD) studies operating one 20 MHz or one 40 MHz RF system as a higher harmonic at the flat-top indicate the beneficial effect on longitudinal beam stability.

## INTRODUCTION

To reach the beam parameters requested for the HL-LHC the PS is being upgraded in the framework of the LHC Injector Upgrade (LIU) project to deliver an intensity of $2.6 \cdot 10^{11}$ particles per bunch (ppb) with 25 ns bunch spacing. In the longitudinal plane the emittance must remain unchanged, hence doubling the longitudinal density with respect to the intensity threshold above which longitudinal coupled-bunch instabilities are observed after transition crossing and at the flat-top [1]. A prototype Finemet cavity [2] has thus been installed as a wide-band longitudinal kicker, driven by a functional prototype of the coupled-bunch signal processing covering all possible dipole oscillation modes [3, 4].

An extensive series of MD studies has been performed in 2016 to understand and resolve technical issues related to the signal processing of the feedback and the Finemet cavity, as well as to explore the performance reach for LHC-type beams with the new feedback system. The technical issues include the frequent trips of the wide-band cavity due to over-current of the power amplifiers and the availability of a maximum number of the in total six acceleration gaps. On the low-level RF side the phasing of the filters of the signal processing and their reliable re-synchronization with respect to circulating bunch train has been treated. The first part of this contribution concentrates on the beam dynamics aspects, covering the measurements of coupled-bunch mode spectra and the maximum intensity reach.

For RF manipulations like bunch splitting and bunch rotation the PS is equipped with high-frequency RF cavities at 20 MHz, 40 MHz and 80 MHz. Due to their narrow bandwidth these cavities cannot sweep with the increasing revolution frequency during acceleration, but can only be operated once flat-top energy has been reached. In the second part results of first studies operating a 20 MHz or 40 MHz cavity as higher-harmonic Landau cavity to longitudinally stabilize the beam at the flat-top are presented.

## INTENSITY REACH WITH FEEDBACK

Maintaining the nominal longitudinal emittance of $\varepsilon_l = 0.35$ eVs per bunch, corresponding to about 4 ns ($4\sigma$ Gaussian fit) bunch length at extraction, the intensity has been increased with the prototype wide-band coupled-bunch feedback. The important stability improvement is illustrated in Fig. 1. At an intensity of $2.0 \cdot 10^{11}$ ppb at extraction, the beam

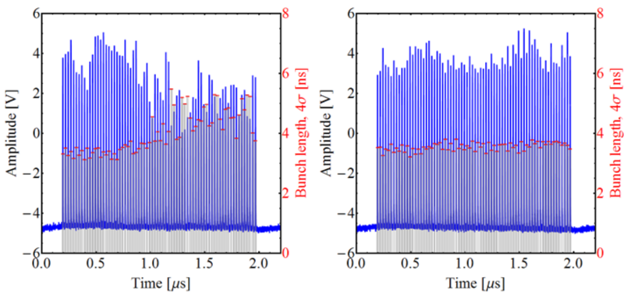

Figure 1: Beam profile during the last turn at $2.0 \cdot 10^{11}$ ppb together with the bunch length along the batch without (left) and with the coupled-bunch feedback switched on (right).

is longitudinally destroyed due to the coupled-bunch instability. Considering the short filling time of the 10 MHz cavities as dominant impedance source, the bunches at the tail of the batch are more strongly affected than the first bunches after the extraction kicker gap. The instabilities are fully suppressed when activating the dedicated feedback system. The bunch length at extraction remains below 4 ns all along the batch and no lengthening is observed for the tail bunches. The longitudinal beam quality reached at $2.0 \cdot 10^{11}$ ppb is equivalent to the beam quality at $1.3 \cdot 10^{11}$ ppb without the coupled-bunch feedback. It is worth noting that this performance has been maintained reliably under operational conditions during the 2016 accelerator run. Slightly higher peak intensity has been reached during short tests.

With the wide-band coupled-bunch feedback even higher intensity has only been achieved with larger longitudinal emittance so far. This emittance is too large for the SPS, but to exclude further longitudinal issues in the PS up to the intensity required for HL-LHC, measurements have been performed up to $2.6 \cdot 10^{11}$ ppb, which corresponds to a total intensity of almost $2 \cdot 10^{13}$ protons per pulse (ppp). Figure 2 shows intensity and transmission during a ramp-up test with a longitudinal emittance of about 0.45 . . . 0.5 eVs.

Even at the intensity as requested at PS extraction for the HL-LHC project, the overall transmission stays at 97 %.

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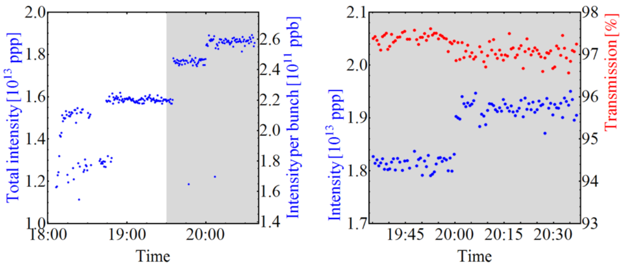


Figure 2: Total intensity together with intensity per bunch during the ramp-up (left), and overall transmission (right, ratio of extracted and sum intensity of both injections).

well above the 5 % loss margin and does not degrade significantly with increased intensity. However, a number of technical difficulties was encountered which complicated the measurements. Only the absolute minimum number of cavity gaps of the 40 MHz (one cavity in straight section SS78) and 80 MHz (two cavities in SS88 and SS89) has been kept open. The remaining cavities would trip due to excessive beam-loading, even in the absence of a voltage program. Additionally, some 10 MHz cavities did not follow their voltage program and indicated an over-current of the final amplifier when tuning them from $h = 20$ to 7 at the end of the flat-bottom [5]. This was solved by activating the 1-turn delay feedbacks only later, at the start of acceleration, to reduce the final amplifier current. Although longitudinal emittance and bunch length required to keep the bunches longitudinally stable at extraction are yet too large for the SPS, the excellent overall transmission and beam quality show that no further show-stopper is in sight to reach the targeted intensity of $2.6 \cdot 10^{11}$ ppb.

## QUADRUPOLE COUPLED-BUNCH OSCILLATIONS

While dipole coupled-bunch oscillations are well damped by the wide-band coupled-bunch feedback when increasing longitudinal density, quadrupole coupled-bunch oscillations can be excited during acceleration and at the flat-top. Figure 3 shows a typical measurement of bunch length oscillations with a phase advance from bunch to bunch observed after transition with an 18-bunch train accelerated on harmonic, $h = 21$. A discrete Fourier transform of amplitudes and phases of the bunch length oscillations reveals the mode spectrum (Fig. 4). The predominant mode number, $n_b = 2$, corresponding to a phase advance of $\Delta\phi = 2\pi n_b/18 = 2\pi/9$, is observed with 18-bunch trains during acceleration. This is very different from the dipole oscillation mode spectrum, where usually the low ($n_b = 1, 2$) and high ($n_b = 16, 17$) modes are strongest [1].

At the flat-top the longitudinal impedance of the PS changes for two reasons. While all 10 MHz cavities are needed during acceleration, the gaps of nine of these cavities are consecutively short-circuited with relays (two relays per cavity) at the flat-top. Secondly, due to the sweeping revolution frequency, the dominant spectral components of

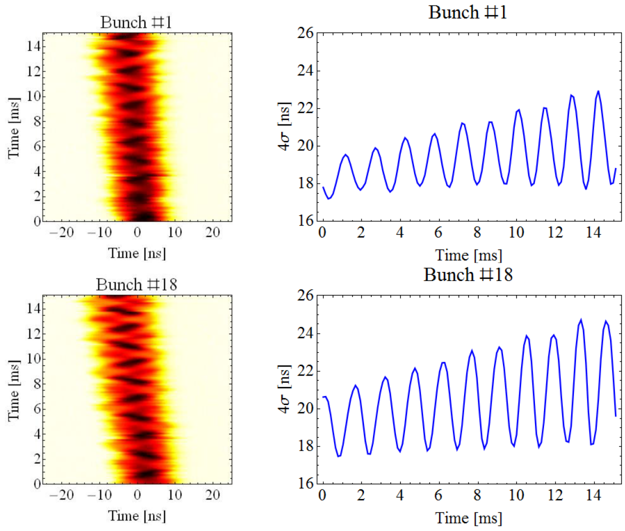


Figure 3: Bunch length oscillations of first and last bunch of an 18-bunch train during acceleration after transition crossing.

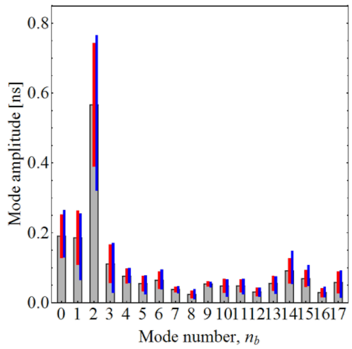


Figure 4: Average quadrupole coupled-bunch mode spectrum of ten cycles during acceleration. The red bars indicate the standard deviation, and the blue bars represent the total spread.

the beam at multiples of the RF frequency ($h = n \cdot 21$, $n = 1, 2, \ldots$) move into the fixed resonances of the RF cavities at 40 MHz ($n = 4$) and 80 MHz ($n = 8$). The quadrupole coupled-bunch spectrum at the flat-top is shown in Fig. 5. Interestingly with the pre-dominant mode numbers around $n_b = 5$, the mode spectrum is extremely similar to the dipole mode spectrum (Fig.6).

## EFFECT OF 80 MHZ CAVITY IMPEDANCE

Part of the measurements have been acquired during parallel proton and lead ion operation. The influence of the impedance of the additional 80 MHz cavity for the bunch shortening with ions, tuned at 230 kHz below the frequency for protons, has been studied. A significant bunch lengthening, notably for bunches at the tail of the batch, becomes evident and had already been observed earlier [6].

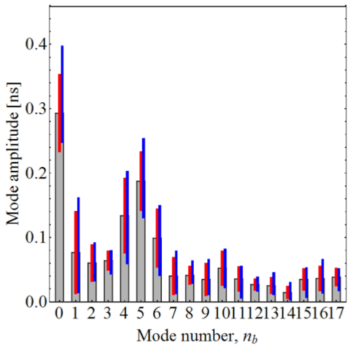


Figure 5: Average quadrupole coupled-bunch mode spectrum of ten cycles at the flat-top.

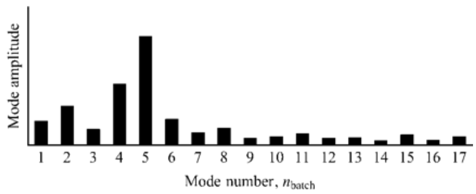


Figure 6: Average dipole coupled-bunch mode spectrum of ten cycles at the flat-top (from 2011 data).

The perturbation due to the impedance from an additional 80 MHz cavity can be directly seen during the last bunch pair splitting from $h = 42$ to 84 at the flat-top and with equivalent intensity of $1.6 \cdot 10^{11}$ ppb (Fig. 7). The high frequency

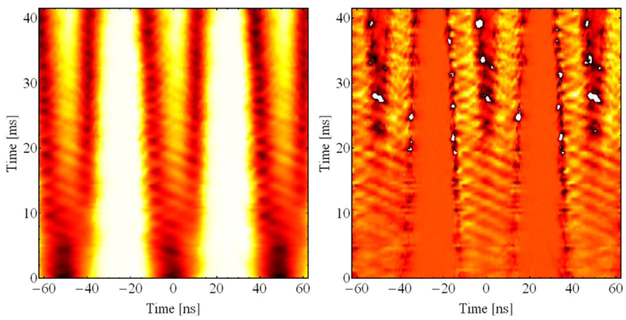


Figure 7: Mountain range plot of the bunch splitting from $h = 42$ to 84 with the gap of the third 80 MHz gap open (left). Averaging and subtracting this from the same data with the third cavity gap closed (right) clearly reveals the high frequency structure.

structure becomes much more pronounced with the gap of the 80 MHz cavity for ion operation open. Additionally, the relative phase of the high-frequency structure remains similar from cycle to cycle, confirming that the perturbation must be induced by the beam.

The degradation of the longitudinal beam quality becomes also evident from the bunch length along the batch at extraction, which is compared for two and three open gaps of 80 MHz cavities in Fig. 8. The average bunch length increases by about 300 ps due to the additional impedance, but up to 600 ps for the bunches at the tail of the batch.

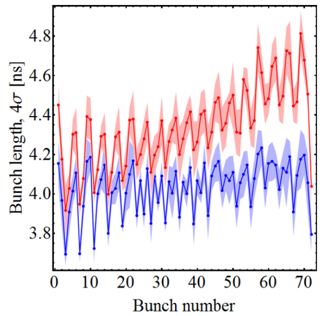


Figure 8: Bunch length along the batch at an intensity of $1.6 \cdot 10^{11}$ ppb with two (blue) and three (red) gaps of 80 MHz cavities open. The shaded areas indicate the spread of the ten cycles taken for the average.

These measurements underline the importance of the multi-harmonic feedback systems for the high-frequency cavities under development in the framework of the injector upgrades.

## LANDAU RF SYSTEM STUDIES

While the PS presently has no tunable RF system that could be operated as a higher-harmonic RF system in addition to the ferrite-loaded cavities at $h = 21$, MD studies have been conducted at the flat-top using a 20 MHz or a 40 MHz at low voltage as a Landau RF system. Stopping the bunch splitting manipulations at the flat-top a beam with an equivalent intensity of $1.3 \cdot 10^{11}$ ppb (respectively four times that intensity without the splittings) develops a coupled-bunch oscillation when held at the low RF voltage of 20 kV at $h = 21$ with a single 10 MHz cavity.

Adding RF voltage at the second harmonic (20 MHz) of the principal RF system yields a slight improvement of the longitudinal stability when the higher-harmonic RF system is in counter-phase (bunch lengthening mode), confirming previous measurements under similar conditions [7].

However, only about 5 kV at $h = 84$ in phase (bunch shortening mode) from a 40 MHz cavity is sufficient to fully stabilize the beam and a significant stability improvement can be measured down to a higher-harmonic voltage as low as 2 kV. This technique is well known from the SPS where it is essential to stabilize the beams for the LHC [8]. With the harmonic number ratio of $84/21 = 4$, the beneficial effect is only seen in phase. Adding higher-harmonic RF voltage in counter-phase has a negligible effect on longitudinal stability as illustrated by the mode spectra shown in Fig. 9.

Figure 10 illustrates the synchrotron frequency distribution for the beneficial case of a harmonic number ratio of four and the given percentage of RF voltage at the higher-harmonic RF system with respect to the principal one. The synchrotron frequency spread is significantly increased in the relevant emittance range of up to $1.4\,\text{eVs} = 4 \cdot 0.35\,\text{eVs}$, even for a moderate voltage in the higher-harmonic cavity.

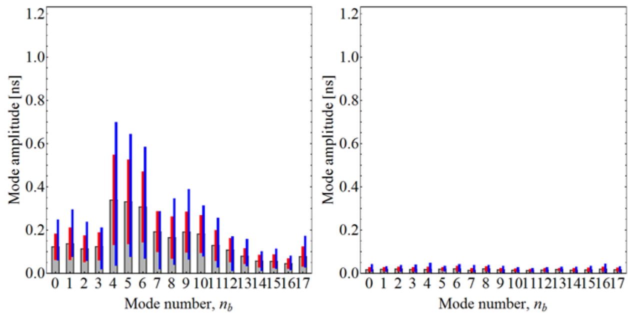


Figure 9: Coupled-bunch mode spectrum at the flat-top with an RF system at four times the fundamental harmonic and 5 kV RF voltage, i.e., one quarter of the 20 kV in the principal RF system. The higher-harmonic voltage has been brought up in counter-phase (left), as well as in phase (right).

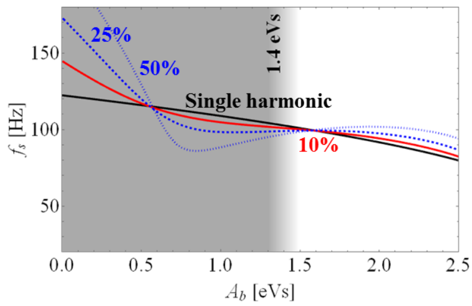


Figure 10: Synchrotron frequency versus single particle emittance for a harmonic ratio of four and different voltage ratios, given in percent of the principal harmonic voltage of 20 kV at $h = 21$. Both RF systems are in phase.

## CONCLUSIONS

The MD campaign with the new wideband coupled-bunch feedback in 2016 has demonstrated that $2.0 \cdot 10^{11}$ ppb with 25 ns spacing and the nominal batch length of 72 bunches can be achieved and maintained under operational conditions. Beyond this intensity the longitudinal emittance must be blown-up further by almost 40 % to keep the beam longitudinally stable up to the intensity of the HL-LHC request of $2.6 \cdot 10^{11}$ ppb. However, accelerating a total intensity of more than $72 \cdot 2.6 \cdot 10^{11}$ ppb $\simeq 1.9 \cdot 10^{13}$ ppb with losses well below 5 % shows that no further longitudinal show-stopper is expected.

Initial studies with higher-harmonic RF voltage from a 20 MHz or 40 MHz cavity indicate the beneficial effect on longitudinal stability depending on the relative phase with respect to the principal RF system. In particular operating a 40 MHz in phase, as used in for LHC-type beams in the SPS, suppresses the coupled-bunch bunch oscillations efficiently. Further studies at higher intensity are foreseen in 2017.

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