LONGITUDINAL COUPLED-BUNCH INSTABILITIES IN THE CERN PS

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Abstract

Longitudinal coupled bunch instabilities in the CERN PS represent a major limitation to the high brightness beam delivered for the LHC. To identify possible impedance sources for these instabilities, machine development studies have been carried out. The growth rates of coupled bunch modes have been measured, and modes have been identified using mountain range data. Growth rate estimations from coupled bunch mode theory are compared to these results. It is shown that the longitudinal impedance of the broad resonance curve of the main 10 MHz RF system can be identified as the most probable source. Several modes are driven simultaneously due to the large width of the resonance, which is considered for the analysis.

INTRODUCTION

Longitudinal coupled bunch (CB) oscillations, especially coupled dipole oscillations of bunches around their reference position, represent a major limitation to the beam intensity and brightness that can be delivered from the CERN PS. To damp or suppress the development of CB instabilities effectively, their excitation mechanism and the source of impedance exciting the beam need to be understood. Machine development (MD) studies have been performed during the machine run in 2006 with a high brightness proton beam, comparable to the brightness of the LHC-type beams in the PS.

The CERN PS is equipped with ten 2.8–10 MHz tunable ferrite-loaded cavities for acceleration, as well as 20, 40, 80 and 200 MHz cavities for RF manipulations and longitudinal emittance blow-up. To simplify the mode identification, seven bunches (full ring) have been injected and accelerated at $h = 7$ (3.05 to 3.34 MHz). The 20, 40 and 80 MHz RF systems were switched off with their gaps short circuited. The CB instabilities start shortly after transition crossing ($\gamma_{\mathrm{tr}} = 6.1$) and develop during acceleration. Firstly, growth rates were measured by analyzing the beam signal around a specific harmonic of the revolution frequency and secondly, the spectrum of the CB modes has been extracted from mountain range measurements.

COUPLED-BUNCH OSCILLATIONS

The indication of CB oscillations are spectral lines of the beam at

$$\omega = (n + lM)\omega_0 + m\omega_s, \qquad (1)$$

where $l = 0, \pm 1, \ldots \pm \infty$, $\omega_{\mathrm{RF}} = h\omega_0$ is the RF frequency at harmonic h, ω_s is the synchrotron frequency and ω_0 is the revolution frequency.

A single bunch can perform dipole ($m = 1$), quadrupole ($m = 2$) and higher order ($m = 3 \ldots \infty$) oscillations of the bunch distribution. Additionally, the oscillation between two bunches may be coupled: all M bunches of a batch oscillate with the same single bunch oscillation type m and amplitude $\hat{\phi}$, but with a constant phase advance of $\Delta\phi = 2\pi n/M$ between bunches; the CB mode number is given by $n = 0 \ldots M - 1$ [1].

A mixture of different CB oscillation modes m, n is generally observed. Selection of a specific mode of interest can be done either by measuring the beam signal within a limited bandwidth only, or by decomposition using a discrete Fourier transform (DFT).

GROWTH RATE MEASUREMENTS

Growth rates of longitudinal CB oscillations can be measured by observing the frequency spectrum of the beam signal from a longitudinal pick-up around the harmonics of the revolution frequency. Parts of the narrow-band CB damping loops for LHC type beams have been used for observation (Fig. 1). The beam signal from a longitudinal pick-up
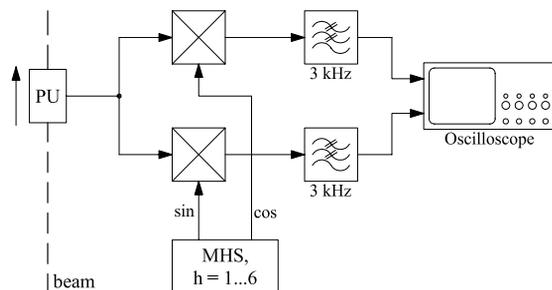

Figure 1: Set-up for the growth rate measurements. The multi-harmonic source (MHS) is a DDS oscillator generating a selectable harmonic of the revolution frequency.

is mixed with a selectable revolution harmonic generated by a DDS oscillator coupled to the revolution frequency of the beam. The base-band I/Q signals are then filtered by a low-pass filter cutting above 3 kHz and recorded with an oscilloscope. A typical measurement is shown in Fig. 2. Transition crossing is clearly visible as a peak of the peak detected beam signal. Thereafter, the base-band signals grow exponentially, indicating a CB instability.
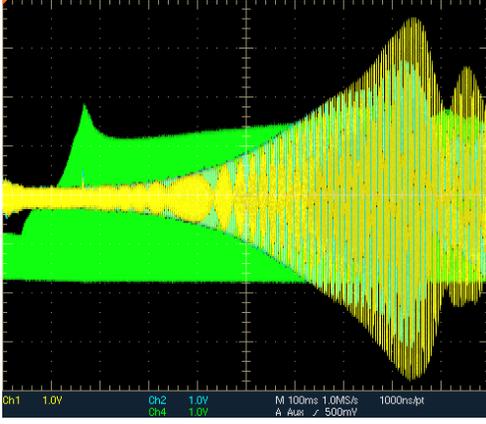
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Figure 2: Growth rate measurements of a CB mode ($n = 2$, 5, $m = 1, 2, \ldots$); $f_s \simeq 0.2\,\text{kHz}$ after transition. Green trace: peak detected beam signal; yellow and blue traces: down-converted base-band signals around the 5th harmonic of ω_0; horizontal scale: 100 ms per division.

The growth rate $1/\tau$ of the CB oscillation is computed from a linear fit to the logarithmic amplitude envelope of the measured signal in the region of exponential growth; saturation is thus not taken into account. The measured growth rates versus longitudinal bunch emittance are plotted in Fig. 3. The emittance is adjusted with a controlled longitudinal blow-up at flat-bottom. Only a very weak de-
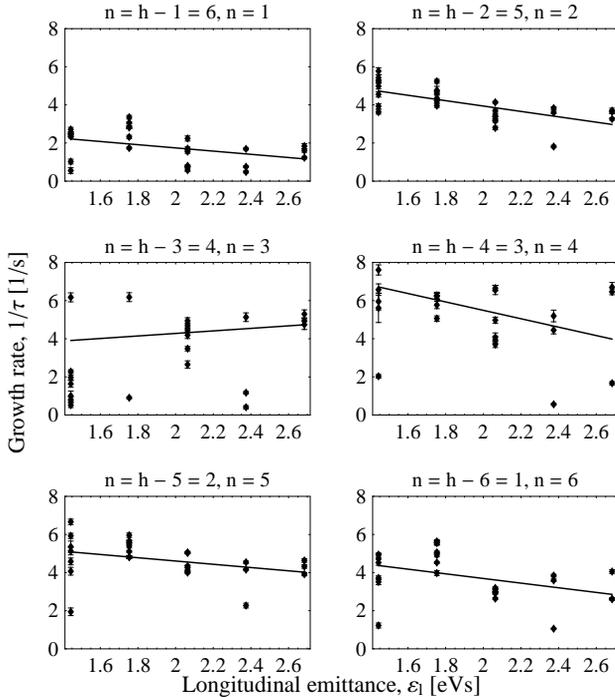

Figure 3: Growth rates $1/\tau$ versus longitudinal emittance ε_l, measured at the harmonics 1 to 6 of ω_0.

pendence of the growth rates on the longitudinal bunch emittance is observed. This indicates an impedance source in the area with flat dependence of the growth rate on bunch

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length (for $m = 1$: $\tau_{\text{bunch}} \simeq 0.5/f_r$). The large scatter of the measurements can be related to small intensity variations of each individual cycle. The $n = 3$ and 4 modes start to develop 200 ms later in the cycle and have larger scatter since the bunches already oscillate on the other modes.

MODE ANALYSIS

The dipole mode CB spectrum at a certain moment in the cycle can be found from mountain range measurements spanning a few periods of the synchrotron oscillation (Fig. 4). In this case, the center positions of the bunches
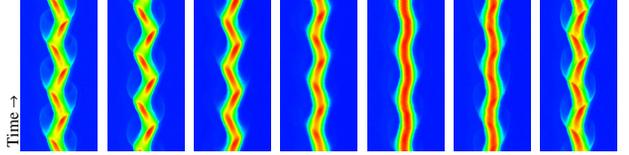

Figure 4: Mountain range density plots (490 ms after transition, see Fig. 2) of all seven bunches during 15 ms ($f_s \simeq 210\,\text{Hz}$). The horizontal span of each frame is 160 ns; the distance between two bunches (reduced) is 304 ns.

versus time is computed from the center position of a Gaussian fit to each bunch in each frame. A nearly sinusoidal motion of the bunch centers with time is observed. A fit of a sinusoidal function to the motion of the bunch centers

$$\hat{\phi}_k \sin(\omega_s t + \theta_k) = \sum_{n=0}^{M-1} \hat{\Phi}_n \sin\left(\omega_s t + \frac{2\pi nk}{M} + \Theta_n\right) \quad (2)$$

results in an oscillation amplitude $\hat{\phi}_k$ (k: bunch index), an oscillation phase θ_k and a frequency, corresponding to f_s. The $n = 0 \ldots 6$ mode amplitudes $\hat{\Phi}_n$ and phases Θ_n are computed applying a DFT according to

$$\hat{\Phi}_n e^{-i\Theta_n} = \frac{1}{M} \sum_{k=0}^{M-1} \hat{\phi}_k e^{-i\theta_k} \cdot e^{2\pi ikn/M} . \quad (3)$$

Fig. 5 illustrates the CB mode spectrum obtained from the mountain range data shown above. This mode spectrum
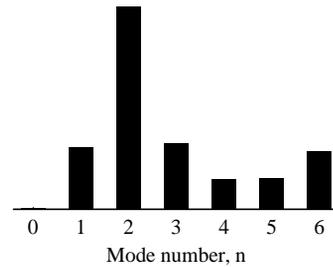

Figure 5: Dipole CB mode amplitudes $\hat{\Phi}_n$ extracted from the mountain range measurement shown in Fig. 4.

is very reproducible. The $n = 2$ oscillation is excited first and has the maximum amplitude.

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SOURCES OF IMPEDANCE

Obvious sources of longitudinal impedance in the PS are the RF cavities. Only the 10 and 200 MHz RF systems were not short-circuited. The frequency of the 200 MHz RF system is too high to explain the dependence on bunch length and the excitation of dipole modes. Therefore, the 10 MHz RF system [2] is the most probable impedance source. A simplified model of the system is sketched in Fig. 6.
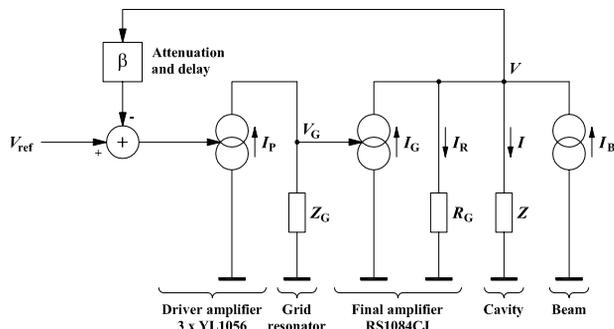

Figure 6: Simplified model of the 10 MHz RF system, including ferrite loaded cavities in the PS and power amplifier with a tuned grid resonator and the fast feedback around the amplifier.

According to this model, the impedance seen by the beam can be written as

$$Z_{\mathrm{c}} = \frac{dV}{dI_B} = \frac{Z_G g_P g_G}{Z_G g_P g_G \beta + (R_G + Z)/(R_G Z)}, \quad (4)$$

where $Z_G(\omega)$ is the impedance of the grid resonator, g_P and g_G are the effective trans-conductances of driver and final amplifier, β represents attenuation and delay of the feedback loop. The parameters of the model have been matched to reproduce the measured open and closed loop transfer functions of six of the ten cavities. The result for $\mathrm{Re}\{Z_c\}$ is shown in Fig. 7.
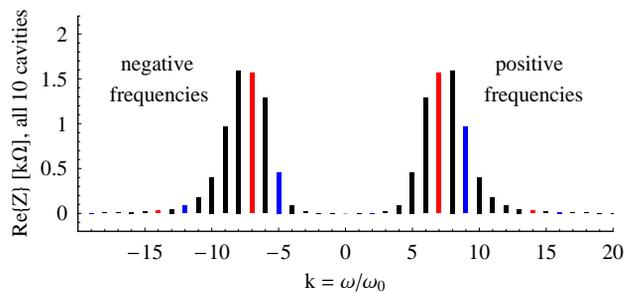

Figure 7: Real part of the total impedance of the 10 MHz cavities at the revolution harmonics.

As the impedance Z_c covers several revolution harmonics around $h\omega_0$, the narrow-band approximation is not applicable for the estimation of the growth rates of the CB oscillations. For dipole modes, the growth rates $1/\tau =$

Im$\{(\Omega - \omega_{s0})/\omega_{s0}\}$ are given by the eigenvalues, λ_k of the system [3, 4]

$$\lambda_k j_k \propto \sum_{l'=-\infty}^{\infty} \frac{Z_c(k')}{k'} j_{k'} \int_{-\infty}^{\infty} \frac{dg(r)}{dr} J_1(k'r) J_1(kr) dr \,. $$
$$(5)$$

The synchrotron frequency in the center of the bunch is given by ω_{s0} and J_1 is the Bessel function of the first order; $k = n + lM$, $k' = n + l'M$; the eigenvector (Fourier transform of the current perturbation) is j_k.

Solving the system Eq. (5) for its eigenvalues λ_k results in the growth rates shown in Table 1. Due to the symme-

Table 1: CB growth rates from eigenvalues of Eq. (5).

Mode number	$n = 1$	$n = 2$	$n = 3$
Growth rate, $1/\tau$	$2.5\,\mathrm{s}^{-1}$	$3.0\,\mathrm{s}^{-1}$	$1.0\,\mathrm{s}^{-1}$

try of Eq. (5), the modes $n = 6, 5, 4$ have the same, but negative growth rates as modes $n = 1, 2, 3$ (Table 1). The measured growth rates are slightly higher. A delayed occurrence of the $n = 3$ mode, when other CB modes are already well developed, may explain the large scattering measured (compare Fig. 3).

CONCLUSION

Longitudinal CB growth rates and mode spectra measurements in the CERN PS indicate that the main 10 MHz RF system represents the most probable impedance source for excitation. Due to the strong feedback, the impedance of the cavities covers 4 harmonics at each side of the RF harmonic. The shape of these impedance lines predicts a $n = 2$ mode being stronger than $n = 1$. This has also been observed with beam. Methods to damp the CB oscillations with a wide-band feedback or by optimizing the cavity impedance with the one-turn-delay feedback are currently studied.

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