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FLAT-BOTTOM INSTABILITIES IN THE CERN SPS

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Abstract

At intensities of 2.6×10^{11} protons per bunch (ppb), required at SPS injection for the High Luminosity LHC beam, longitudinal instabilities can degrade the beam quality delivered by the SPS, the LHC injector at CERN. In this paper, we concentrate on beam instability at flat bottom. The dependence of the instability threshold on longitudinal emittance and LLRF system settings was measured, to help identify the impedance driving this instability. While reducing the longitudinal emittance reduces the losses at injection, it can drive the beam unstable. The LLRF system of the SPS (partially) compensates beam loading, but also affects the instability. The effect of the different LLRF systems (feedback, feedforward, phase loop and longitudinal damper) and the fourth harmonic RF system on the instability was investigated. The measurements are compared to particle simulations performed with the longitudinal tracking code BLonD.

INTRODUCTION

The SPS is the injector to the LHC and presently operates at a nominal LHC intensity of 1.15×10^{11} ppb. Instabilities, beam loading, and intensity-dependent losses limit the achievable intensity in the present SPS [1]. However, the High Luminosity LHC project demands that 2.6×10^{11} ppb are injected into the SPS with a loss budget not larger than 10% [2]. The LHC Injectors Upgrade (LIU) project aims at achieving these goals. In the SPS, several improvements will be implemented during the ongoing Long Shutdown 2 (LS2) and include impedance reduction, a reorganization of the main accelerating Traveling Wave Cavities (TWC) to reduce beam loading, and an upgrade of the RF power and low-level RF (LLRF) system [3]. Capture and flat-bottom losses as well as their mitigations are discussed in [4], while instabilities during ramp were recently considered in [5]. The TWCs are equipped with 630 MHz Higher-Order Mode (HOM) couplers to mitigate these instabilities and additional HOM couplers will be installed during LS2. However, they also lead to a detuning of the fundamental passband. Here, we discuss the effect of this detuning on beam stability at flat bottom.

MEASUREMENTS

During measurements in 2018, 48 bunches with 25 ns spacing and 2.2×10^{11} ppb were found to be unstable at flat bottom. The 200 MHz TWC impedance was assumed to drive this instability. Since the present RF system is power limited at these intensities, full intensity scans were not possible. Therefore, we performed intensity studies with only 12 bunches. This is well below the nominal 72, and recently operational 48, bunches, but did allow measurements without the feedback system active. These measurements were used to benchmark longitudinal tracking simulations, then also applied for future scenarios.

Figure 1 shows an example of the $4\sigma_{\mathrm{FWHM}}$ bunch length evolution along a 19.2 s long flat bottom, where an instability develops at 8 s. Here, $4\sigma_{\mathrm{FWHM}}$ denotes the Gaussian equivalent 4σ of the FWHM bunch length. Notice that all bunches become unstable, since both the minimum and maximum bunch length increase. This coupling of the head of the batch with its tail is likely due to the beam phase loop, which averages over 12 bunches, and it was not observed when the phase loop was off.

We consider the beam to be unstable, if the average bunch length exceeds the threshold bunch length τ_{th}, defined as the average maximum bunch length between 40 and 100 ms after injection, i.e.

$$\langle 4\sigma_{\mathrm{FWHM}}\rangle_{\mathrm{bunches}} > \tau_{\mathrm{th}} \coloneqq \langle \max 4\sigma_{\mathrm{FWHM}}\rangle_{40\mathrm{ms}\ldots100\mathrm{ms}} \,. \quad (1)$$

This criterion is also applied in simulations.

Figure 2 shows the measured beam stability for different bunch lengths and intensities for 12 bunches in single RF and with only the phase loop active. For better comparison with simulations, only data up to 10 s was used. Above 1.2×10^{11} ppb the beam becomes unstable. However, once the one-turn delay feedback (OTFB) is turned on to reduce the beam loading of the main 200 MHz TWCs, beams up to 2.2×10^{11} ppb become stable. This gives a strong indication that the flat-bottom instability is driven by the main impedance of the 200 MHz TWC.

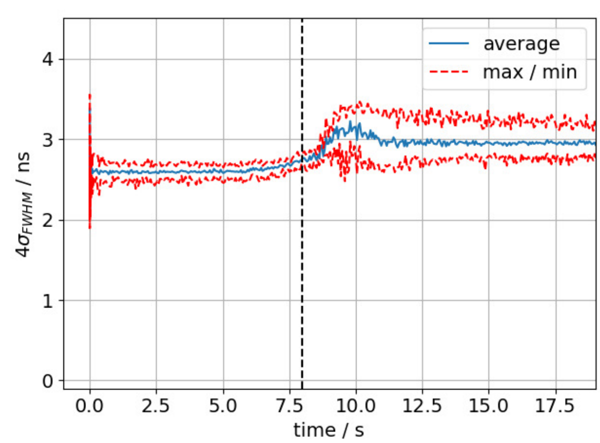

Figure 1: Measured $4\sigma_{\mathrm{FWHM}}$ bunch length of 12 bunches at flat bottom. The vertical dashed line indicates the time at which the threshold condition in Eq. (1) is satisfied.

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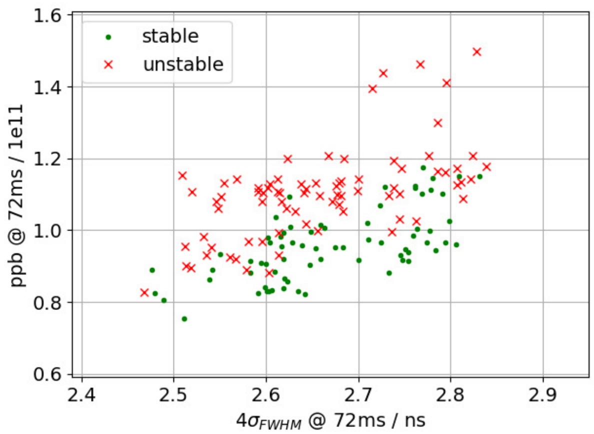

Figure 2: Measured instability thresholds as a function of bunch length for 12 bunches without feedback. With feedback on, beams were stable up to 2.2×10^{11} ppb.

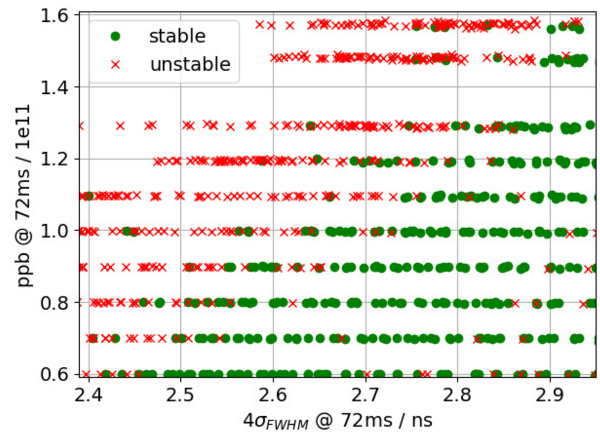

Figure 3: Simulated instability thresholds for 12 bunches on a 10 s flat bottom without feedback.

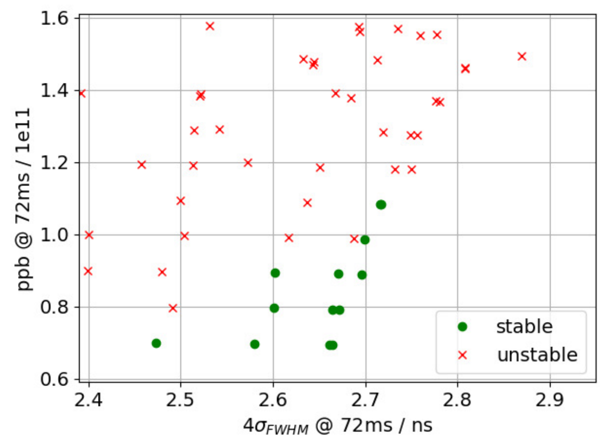

Figure 4: Simulated instability thresholds for 12 bunches on a 10 s flat bottom without feedback and with shifted resonance frequency of the main TWCs .

SIMULATIONS

Simulation Setup

To simulate the longitudinal beam dynamics, we used the tracking code BLonD [6]. It is a modular code that allows to include multiple RF systems, induced voltage due to impedance sources, as well as a model of the LLRF system of the SPS. For the initial bunch distribution, we simulated the longitudinal bunch rotation in the PS, the injector of the SPS. Using rotated bunches instead of matched bunches is important for two reasons. First, the bunch rotation creates halo particles [7], which lead to capture losses in the SPS [4]. Second, using matched bunches gives an instability threshold that is significantly above the one observed [5]. An accurate model of the LLRF system is required as well. Here, we include the beam phase loop and feedback. The latter is implemented by an impedance reduction factor (see [8]), but a dynamic implementation is available in BLonD as well. Finally, we used the full SPS impedance model [9].

A simulation of 12 bunches on a 10 s long flat bottom requires tracking over 432 000 turns. With two million macroparticles per bunch, this usually lasts one day on a single computing node. To speed up the computation time, we used the distributed MPI (Message Passing Interface) version of BLonD, that allows multiple computing nodes to communicate and cooperatively execute a simulation. In BLonD-MPI, each node is assigned only a subset of the macro-particles, on which it does the tracking for one turn and computes a partial beam profile. The partial profile is then communicated to the other nodes. Each node then uses the complete profile to compute the induced voltage, applied to its macro-particles in the next turn. For the SPS flat-bottom simulations, using BLonD-MPI with four nodes results in a speedup factor of 20 and reduces the computation time to one hour.

Simulation Results

Figure 3 shows the simulated instability thresholds for 12 bunches on a 10 s long flat bottom. The overall picture agrees with the measured one in Fig. 2. However, closer inspection reveals that some simulated beams are stable at intensities of 1.2×10^{11} ppb and above, while all measured beams were already unstable at these intensities.

These simulations were performed without taking into account the detuning of the main TWCs due to the 630 MHz HOM couplers. Without HOM couplers, the resonant frequency of the TWC is at f_r = 200.222 MHz [10]. The HOM couplers lead to a resonant frequency shift Δf_r of -90 kHz and -130 kHz for the two long and two short TWCs, respectively. Figure 4 shows that the simulated instability thresholds with this frequency shift included are reduced and agree better with measurements.

Post-LS2, due to improved HOM damping, the TWC detuning is expected to be -210 kHz and -170 kHz for the

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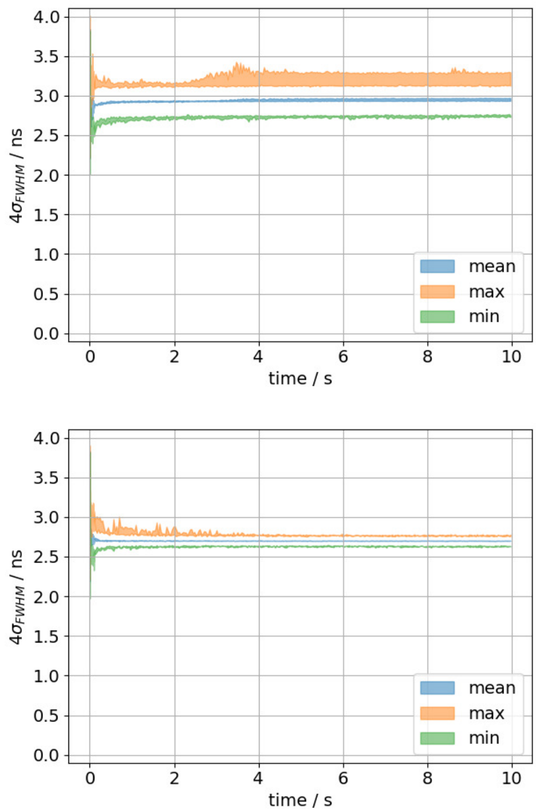

Figure 5: Simulated bunch length for 48 bunches with 2.6×10^{11} ppb in single RF system (top) and with double RF system with 0.1 voltage ratio (bottom). The shaded regions indicate the spread for simulations with different seeds.

modified long and short TWCs, respectively. For these detunings, Figure 5 shows the simulated bunch lengths for 48 bunches with 2.6×10^{11} ppb in nominal optics Q20 ($\gamma_{\mathrm{tr}} = 18$) and post-LS2 SPS. When only a single RF system is used, individual bunches become unstable (top). The beam can be stabilized by using an 800 MHz RF system with a voltage ratio of $V_{800}/V_{200} = 0.1$ in bunch-shortening mode (bottom). However, this mechanism proves insufficient when using optics Q22 with larger transition energy ($\gamma_{\mathrm{tr}} = 20$) considered for beam loading alleviation during ramp.

COUPLED BUNCH INSTABILITY

For $M = 924$ equally spaced bunches and a narrow-band impedance Z close to an integer multiple of the revolution frequency f_{rev}, the growth rate $\mathrm{Im}\Omega$ of bunch oscillation multipole $m = 1, 2, 3, \ldots$ and coupled bunch mode $n = 0, 1, \ldots M-1$ can be obtained from the eigenvalues of a 2×2 matrix and is approximately proportional to (see e.g.[11])

$$\mathrm{Im}\Omega \propto \frac{\mathrm{Re}Z_{p_1}}{p_1} + \frac{\mathrm{Re}Z_{p_2}}{p_2} \simeq \frac{\mathrm{sinc}^2\left[\frac{\tau}{2}(\Delta f_r - n f_{\mathrm{rev}})\right]}{h+n} - \frac{\mathrm{sinc}^2\left[\frac{\tau}{2}(\Delta f_r + n f_{\mathrm{rev}})\right]}{h-n} \tag{2}$$

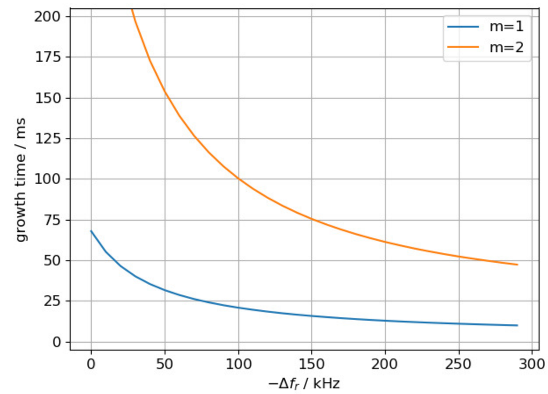

Figure 6: Coupled bunch instability growth time versus TWC detuning Δf_r for multipoles $m = 1, 2$.

Here, h denotes the harmonic number and we used the analytical expression for a TWC impedance with filling time τ [10], evaluated at the two frequencies $p_{1,2} f_{\mathrm{rev}} \simeq \pm f_r$. For small Δf_r, Eq. (2) increases linearly with Δf_r, and has a finite value at zero detuning (except for $n = 0$). The growth time of the dominant mode $n = 12$ was computed from the 2×2 matrix for a binomial bunch distribution and is shown in Fig. 6 for the dipole ($m = 1$) and quadrupole ($m = 2$) modes. Note that these numbers are only qualitative, since the assumption of $M = 924$ bunches, spaced 25 ns apart, is not fulfilled. Nonetheless, we see that the dipole mode has the smallest growth time, which decreases with larger detuning like $1/\Delta f_r$, in agreement with the approximate result in Eq. (2). The growth times at zero additional detuning Δf_r are not given by the constant term in Eq. (2), because the RF-frequency at flat bottom is 200.265 MHz and, thus, not an exact integer multiple of f_r. Notice that there is only a mild dependence on Δf_r for the relevant detuning range between 100 and 200 kHz.

CONCLUSION

Measurements of the instability thresholds for 12 bunches with and without the OTFB strongly indicate that the flat-bottom instability is driven by the impedance of 200 MHz TWCs. The 630 MHz HOM couplers, required to mitigate instabilities during ramp, lead to a detuning of the pass-band of the 200 MHz TWCs, which lowers the instability thresholds at flat bottom. The detuning is expected to be even larger after LS2, but simulations of 48 bunches with 2.6×10^{11} ppb in the post-LS2 SPS show that the beam can be stabilized by the 800 MHz RF system.

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