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UNCONTROLLED LONGITUDINAL EMITTANCE BLOW-UP DURING RF MANIPULATIONS IN THE CERN PS

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Abstract

The CERN Proton Synchrotron (PS) determines the basic bunch spacing for the Large Hadron Collider (LHC) by means of rf manipulations. Several rf systems in a frequency range from 2.8 MHz to 200 MHz are available for beam acceleration and manipulations. Each of the six bunches injected from the PS Booster is split in several steps into 12 bunches spaced by 25 ns, yielding a batch of 72 bunches at transfer to the Super Proton Synchrotron (SPS). In the framework of the LHC Injector Upgrade (LIU) project the bunch intensity must be doubled. However, with most of the planned upgrades already in place this intensity has not yet been achieved due to collective effects. One of them is uncontrolled longitudinal emittance blow-up during the bunch splittings. In this contribution, measurements of the blow-up during the splitting process are presented and compared with particle simulations using the present PS impedance model. Beam-based measurements of the impedances of the rf cavities have been performed. They revealed that to reproduce the instability an additional impedance source is required in the PS impedance model.

INTRODUCTION

One of the requirements of the High Luminosity-LHC (HL-LHC) project at CERN is to double the beam intensity. This target is challenging for the injectors, which are being upgraded in the framework of the LIU project. The PS is the second synchrotron in the injector chain and accelerates the beam up to p = 26 GeV/c before extraction to the SPS, the LHC injector. The beam intensity extracted from the PS for the LHC is $N_b = 1.3 \times 10^{11}$ protons per bunch (p/b), and the LIU target is $N_b = 2.6 \times 10^{11}$ p/b with the same longitudinal emittance.

The role of the PS is also to define the bunch spacing. To do so, several rf cavities of different harmonics, h, are available to perform rf manipulations like bunch splitting or merging, batch compression and controlled longitudinal emittance blow-up. The nominal beam for LHC is produced by injecting 6 bunches from the PS Booster, which are then split in several steps to a batch of 72 bunches with a bunch spacing of 25 ns and a longitudinal emittance of 0.35 eVs at extraction to the SPS. This paper focuses on the consecutive double splittings from the rf harmonic $h = 21$ to $h = 84$ as illustrated in Fig. 1 (left).

The present intensity limit in the PS to preserve good beam quality is $N_b = 2.0 \times 10^{11}$ p/b. Above this threshold, the beam suffers from various collective effects like coupled-bunch instabilities [1] and uncontrolled longitudinal emittance blow-up. A possible source of uncontrolled emittance

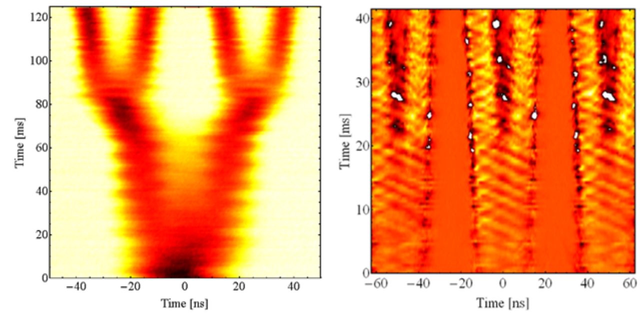

Figure 1: Double splittings at PS flat-top from $h = 21$ to $h = 84$. During this manipulation the beam is split from 18 bunches to 72 bunches with 25 ns bunch spacing (left). Bunches present a 80 MHz structure during the second splitting with three 80 MHz cavity gaps opened (right).

blow-up is the microwave instability, which is driven by high frequency impedance sources for which $f_r \tau_L \gg 1$ and where τ_L is the bunch length. In the PS, the main contributors to the impedance of the machine are the rf cavities.

Table 1: Parameters of the 80 MHz Cavities in PS. The impedance is reduced during normal operation by a direct wideband feedback [2].

Name	Number	R_s/Q [Ω]	R_s [kΩ]	Q
C80	3	56	5.6	100

Amongst the high frequency cavities available in the PS, the 80 MHz cavities are one of the most important contributors (two cavities with $h = 168 \rightarrow f_r = 80.1$ MHz and one cavity tuned for ion operation on $h = 169 \rightarrow f_r = 79.9$ MHz). Those cavities are used for bunch shortening before extraction to the SPS. The characteristics of the 80 MHz cavities in terms of shunt impedance R_s and quality factor Q are shown in Table 1. The gap of the cavities can be mechanically closed during operation when not in use. In dedicated proton operation, only two 80 MHz cavities are open while the third one is needed only during ion operation periods.

During Machine Development (MD) sessions, a perturbation of the bunch profile was observed when the third 80 MHz cavity gap was opened, as shown in Fig. 1 (right) [3]. The impedance of the 80 MHz cavities was then identified to contribute to uncontrolled emittance blow-up in the PS. However, first particle simulations using the impedance parameters in Table 1 were not able to reproduce measurements. Therefore, investigations were launched to re-evaluate the impedance of the cavities by performing beam-based measurements.

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SIMULATIONS OF RF MANIPULATIONS

Measurements of the longitudinal emittance along the batch during double splittings were performed for a bunch intensity of $N_b = 2.0 \times 10^{11}$ p/b. The longitudinal emittance was then evaluated from the measured bunch length at different stages of the splittings. An example with the third 80 MHz cavity gap opened is shown in Fig. 2. The longitudinal emittance along the batch stays reasonably constant after the first splitting. However, the longitudinal emittance increases along the batch after the second splitting. This pattern is not seen if the third 80 MHz cavity gap is closed, indicating that this impedance indeed contributes to emittance blow-up.

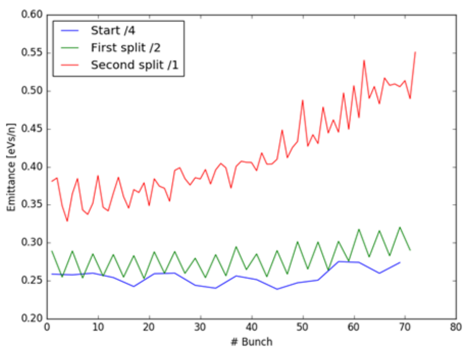

Figure 2: Measured longitudinal emittance blow-up along the batch during double splittings with the three 80 MHz cavity gaps open.

Simulations of the rf manipulations with intensity effects were performed using the BLonD simulation code [4] with the 80 MHz cavity impedance model from Table 1 together with an inductive impedance of $\text{Im}\, Z/n = 18.4\ \Omega$ [5]. However, initial simulations were not able to reproduce the observations. The 80 MHz cavities impedance in simulations was then increased to find the required impedance to match measurements, as shown in Fig. 3. The impedance was increased by multiplying the shunt impedance R_s or by increasing both R_s and Q keeping R_s/Q constant. Both options gave the same results. The criteria to match simulations with measurements are that the emittance blow-up should be present only with three cavity gaps opened and not two, and that the emittance blow-up occurs only during the second splitting. This configuration is obtained if the impedance is multiplied by a factor from 2 to 2.3.

One important outcome of the simulations is that at $N_b = 2.6 \times 10^{11}$ p/b even two cavities could be sufficient to drive uncontrolled emittance blow-up if the impedance is indeed under evaluated. A reliable impedance model for 80 MHz cavities is therefore needed.

MODULATION OF BEAM PROFILE WITH RF OFF

The first approach to evaluate the 80 MHz cavity impedance consisted in measuring the modulation of the beam profile during slow debunching with rf off. This

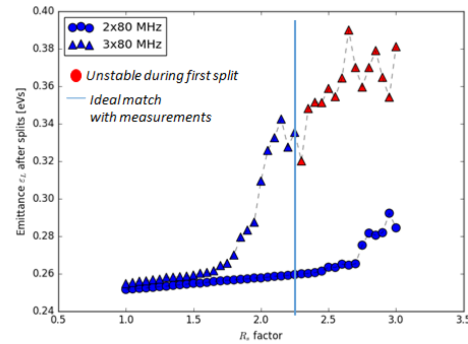

Figure 3: Maximum emittance along the batch in particle simulations, scanning the 80 MHz cavity impedance factor with two or three gaps open. The match with measurements is the vertical blue line.

method was successfully applied over many years in the SPS to identify the impedance sources responsible of microwave instability [6]. The method consists of measuring the modulation of the beam profile with large bunch length so that impedance sources fulfill the condition $f_r \tau_L \gg 1$. Moreover, the momentum spread should be as small as possible to ensure slow debunching. Measurements were performed at the PS flat top by reducing iso-adiabatically the rf voltage to zero, ensuring both large bunch length and small momentum spread. For a mono-energetic coasting beam and a narrow-band impedance source, the growth rate is [7]

$$\text{Im}\,\Omega = \frac{e\omega_0}{2}\left(\frac{N_{\text{tot}}\eta}{\pi\beta^2 E}\omega_r R_s\right)^{1/2}, \qquad (1)$$

where N_{tot} is the total beam intensity, η is the phase slip factor, β is the particle relativistic velocity factor and E is the beam energy (total).

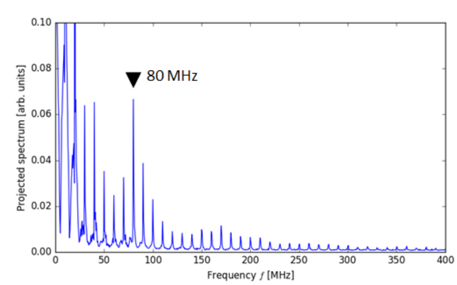

Figure 4: Measured beam profile modulation with rf off in frequency domain. The projected spectrum corresponds to the maximum amplitude of the spectrum modulation.

In the PS, measurements were performed using a multi-bunch beam (3 to 21 bunches with $N_b = 1.3 \times 10^{11}$). It is expected for a multi-bunch beam that Eq. (1) is applicable in first approximation and that the parameter of interest is R_s rather than R_s/Q. This is in agreement with the simulation results presented in the previous section. To compare the measurements with particle simulations, the maximum peak amplitude of the beam spectrum is a more reliable criterion

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than the growth rate [7]. An example of a measured projected beam spectrum is shown in Fig. 4. This acquisition was done with two 80 MHz cavity gaps opened, and the peak at 80 MHz is clearly visible. This peak disappears when one 80 MHz cavity gap is closed, confirming that the peak is due to the impedance of those cavities. The measured maximum peak amplitude as a function of the number of bunches is shown in Fig. 5.

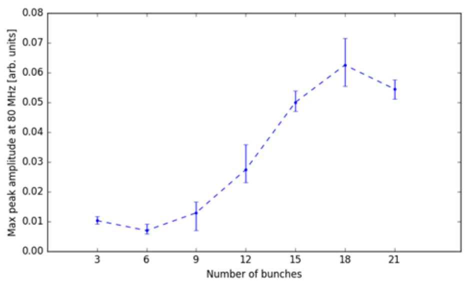

Figure 5: Maximum peak amplitude at 80 MHz in measurements of the projected beam spectrum with rf off. Values below 0.02 are below noise level.

Particle simulations were performed using the same model as described above and results are shown in Fig. 6. To match the simulations with the measurements, the shunt impedance of the 80 MHz cavities should again be multiplied by at least a factor of 2 depending on the number of bunches, which is a second indication that the shunt impedance in the model is maybe under evaluated.

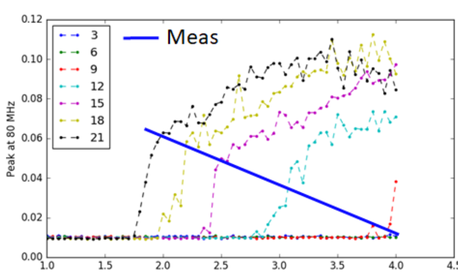

Figure 6: Simulated peak amplitude at 80 MHz, obtained from scanning the impedance factor of the 80 MHz cavities to find the value matching measurements (in blue) for different number of bunches (dotted lines).

MEASUREMENT OF THE INDUCED VOLTAGE IN THE GAP

The impedance of the cavities was evaluated by measuring directly the beam induced voltage in the gap. The induced voltage is

$$V_{\text{ind}}(t) = -eN_b\mathcal{F}^{-1}\left[\sigma(f)\cdot Z(f)\right], \tag{2}$$

where σ is the beam spectrum normalized to the number of bunches. The same method was already applied in the PS to evaluate the impedance of the 10 MHz cavities [8].

The induced voltage was measured at a probe in the cavity (output coupler used as cavity return for beam control) using an oscilloscope. The probe attenuation was calibrated using the measured voltage during pulse, for which the amplitude was evaluated from the quadrupolar oscillations of a mismatched bunch (using tomographic reconstruction [9]). The beam spectrum was measured using a wall current monitor, at the same time as the induced voltage and calibrated with the DC beam current transformer for each acquisition. An example of induced voltage measurement in time domain together with the beam profile is shown in Fig. 7 (left).

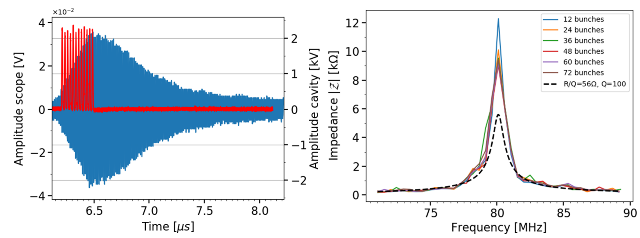

Figure 7: The left plot is an example of measured induced voltage in the 80 MHz cavity (blue) together with the measured longitudinal beam profile (red). The induced voltage is deconvolved with the beam spectrum to get the cavity impedance in the right plot (for one cavity).

Measurements of the cavity impedance were performed for all 80 MHz cavities and for a variable number of bunches (from 12 to 72), in a configuration where the effect of the direct wideband feedback is supposed to be maximum. The measured impedance of the 80 MHz cavities is compared to the expected one in Fig. 7 (right). The deconvolution was only done for the spectral peaks to discard the noise. For all 80 MHz cavities, the measured shunt impedance is at least twice larger than the expected one, in good agreement with the results from the previous section.

CONCLUSIONS

The impedance of the high frequency cavities in the PS and especially the 80 MHz type can drive uncontrolled longitudinal emittance blow-up during rf manipulations and can be an important limitation to reach the HL-LHC beam parameters due to losses during PS-SPS transfer [10]. The present knowledge of the impedance of the cavities is not sufficient to explain the measured blow-up. Nevertheless, various methods of beam measurements of the impedance indicate that at least a factor of 2 in the shunt impedance could be missing and needs to be confirmed. An evaluation of the other impedance sources is also ongoing to improve the overall PS impedance model and find other candidates [11, 12]. A Multi-Harmonic RF Feedback (MHFB) is being implement on all high harmonic cavities in the PS to reduce their impedance.

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