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BEAM LOADING COMPENSATION IN THE SPS 200 MHZ CAVITIES. MEASUREMENTS AND COMPARISON WITH EXPECTATIONS*

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Abstract

The High-Luminosity LHC (HL-LHC) project requires a doubling of the proton intensity transferred from its injector (SPS). Beam loading compensation in the SPS 200 MHz cavities is essential to limit losses when the beam is transferred into the LHC 400 MHz RF system. The SPS Low Level RF (LLRF) has been completely redesigned during the LHC Long Shutdown 2 (LS2, 2019 – mid 2021). The new system relies on a One-Turn delay Feed-Back (OTFB) and a Feed-Forward for regulating the cavity field. The paper presents the performances achieved with the 2023 beam and compares these to the simulations performed during LS2. It also extrapolates the 2023 results to the HL-LHC beam intensity.

MOTIVATION

The fundamental impedance of the SPS 200 MHz cavities has long been recognized as a limitation. It is responsible for coupled-bunch longitudinal instabilities with the high-intensity beam required by the LHC [1]. As the cavities are of the Travelling-Wave type, the beam induced voltage scales quadratically with the length (number of cells) while the accelerating voltage scales linearly (at constant amplifier drive) [2]. The layout was therefore changed: From a set of four cavities consisting of two 4-sections (one section consists in eleven cells) and two 5-sections, we now have four 3-sections and two 4-sections cavities [1]. The old amplifiers power the 3-sections cavities. Two new amplifiers with higher output power are installed on the 4-sections. The available power is 1 MW and 1.6 MW respectively, with 100% AM modulation at the revolution frequency and 50% duty cycle. As part of the LLRF upgrade the regulation of the cavity field was redesigned with the goal of improving the impedance reduction at least a factor of two [3]. The purpose of this paper is to present the results achieved so far with the highest available bunch intensity in the SPS today (1.9×10^{11} ppb), to compare these with the simulations and projections published in previous work [4], and to extrapolate to the anticipated performances with the HL-LHC 2.3×10^{11} ppb intensity.

UPGRADED LLRF PERFORMANCE

The system performance was measured in 2023 with a 72-bunches batch, 25 ns bunch spacing (resulting in 1.8 µs batch length), 1.9×10^{11} ppb, at 450 GeV/c (200.395 MHz RF frequency), just before (possible) transfer to the LHC. The bunch length was measured to be below 1.6 ns (see below). In the following calculations we assume a bunching factor of one resulting in an RF component of beam current equal to 2.44 A. The beam was accelerated using all SPS systems operational for HL-LHC beams: Combination of the fundamental 200 MHz plus the harmonic 800 MHz system used in bunch shortening mode [1], longitudinal emittance blow-up during the ramp [5]. The total 200 MHz voltage was limited to 8 MV during the test, somewhat lower than the 10 MV considered for the HL-LHC era [4]. We will now present the measurements in the two types of 200 MHz cavities.

3-sections Cavities

Cavities 1,2,4 and 5 are of the 3-sections type. We show cavity 1 as an example. The beam induced voltage is 1.16 MV to be compared to the demanded voltage of 1.007 MV. Although the stable phase is 180 degrees (no acceleration at SPS-LHC transfer), the beam loading is not strictly in quadrature with the demanded voltage due to the small cavity detuning (centre frequency 200.1 MHz [6]). The beam loading is at plus 73.7 RF degrees with respect to the demanded voltage. The SPS power amplifiers do not have the capability to deliver the required HL-LHC power in CW (that is during the full SPS turn). As the beam covers maximum 8 µs out of the 23 µs revolution period, the amplifiers are operated in 100% AM modulation with a 50% duty cycle: They are off for half the turn [7]. This mode is possible because the 200 MHz cavities are of the Travelling-Wave type with a filling time below 650 ns. The nominal HL-LHC beam consists of four 72 bunches batches spaced by 225 ns. During the 2023 test we had only one 1.8 µs long batch. Figure 1 displays one machine turn (23 µs). The dotted trace in the top window shows the measured cavity voltage. It is 100% AM modulated, reaching the 1.007 MV during the beam passage. The middle plot shows the uncompensated beam loading (difference between measured and demanded voltage) demodulated in I/Q coordinates. The beam passage (1.8 µs long batch) is identified by the violet dotted trace. The voltage transients caused by the AM modulation are irrelevant for beam quality as they happen outside the beam segment. Beam loading corresponds to the range marked in violet dots. The beam induced voltage is indeed mainly in quadrature (orange trace,Q) resulting in the ± 120 kV uncompensated beam loading at the head and tail of the batch. This is by far the major uncompensated transient during the batch, and results in the corresponding bunches (first and last) being shifted w.r.t. to the LHC receiving buckets by about 0.1 radian (6 degrees), in opposite directions. Even for these marginal bunches the regulation still reduces the

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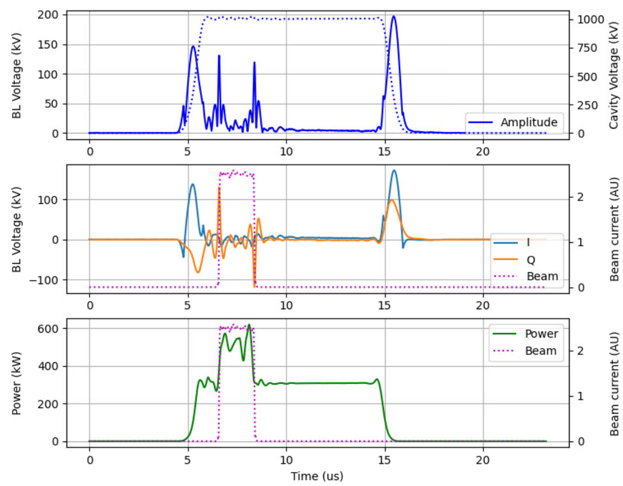

Figure 1: Uncompensated beam loading amplitude (top) and I,Q (middle). Amplifier power (bottom). The AM modulation is in dotted-blue (top). The beam is in dotted-violet (middle, bottom). Three-sections cavity (C1).

beam induced voltage by a factor 10 linear (from 1.16 MV to 120 kV). The blue trace in the top window plots the modulus of the uncompensated beam loading. The reduction in the core of the batch is around 50 linear (1.16 MV reduced below 20 kV). The bottom plot gives the amplifier power measurements. The no-beam plateau is 310 kW, to be compared to the analytical value (based on cavity model) of 278 kW. During the beam passage it reaches 510 kW average, compared to a steady state calculated 466 kW (assuming full ring with same local beam current). The power overshoots to 620 kW, that is 22% (in power) above the 510 kW average. It is interesting to compare these performances with the expectations. In [4] we have studied the HL-LHC scenario that differs from this test by a 21% higher bunch intensity (2.3×10^{11} ppb vs. 1.9×10^{11} ppb) and 25% higher total voltage (10 MV vs 8 MV). In that study the overshoot in required RF power was estimated at 33% (from 665 kW to 885 kW, Fig.18 of [4]). Given the ± 20% precision of the SPS power measurements, the 2023 results agree well with the HL-LHC expectations. The measurements are similar in the other 3-sections cavities.

4-sections Cavities

Cavities 3 and 6 are of the 4-sections type. We take cavity 3 as an example. Being longer, these cavities have both higher demanded voltage (1.874 MV for C3) and higher beam loading (2.06 MV beam induced voltage, 68.2 RF degrees w.r.t. demanded voltage). Refer to Fig. 2. The top and middle plots show the uncompensated beam induced voltage. The peaks are mainly in quadrature (Q) at the head and tail of the batch. They reach 150 kV that, compared to the 1.874 MV demanded voltage, results in a phase deviation of 0.09 rad (5 RF degrees). The bottom trace shows the amplifier power. The no-beam plateau is 650 kW, to be compared to the analytical value of 560 kW. During the beam passage it reaches 780 kW average, compared to a "steady state" calculated 777 kW. Given the large uncertainty on our power measurements, these numbers are not concerning. The power overshoots to 1260 kW, that is 62% higher (in power), significantly more than the simulations (23%). We will address this in the conclusion.

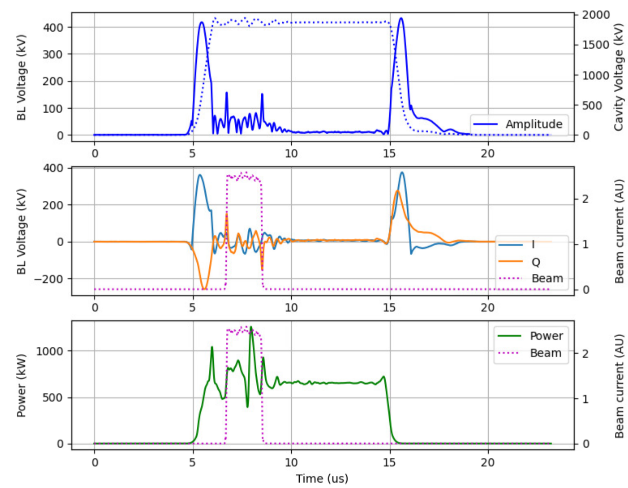

Figure 2: Uncompensated beam loading amplitude (top) and I,Q (middle). Amplifier power (bottom). Four-sections cavity (C3).

BEAM QUALITY

For a lossless transfer of the SPS bunches into the 400.8 MHz LHC buckets, two parameters are very important, the bunch length and bunch phase. The measured bunch length along the batch gave measurements between 1.40 and 1.57 ns, that is within the HL-LHC specifications (less than 1.6 ns [1]). Figure 3 shows the bunch position along the batch. For each bunch it gives the deviation with respect to the even spacing equal to five RF periods. Of course the bunches are located at the centre of each bucket, resulting in a modulation of the bunch position following the phase of the uncompensated beam loading presented above. The largest deviations are (logically) observed for the first and last bunches of the batch. The first bunch is offset by 70 ps, while the last one is shifted by -70 ps. This corresponds to 10 RF degrees (200 MHz) pk-pk. It is interesting to compare this result to the HL-LHC expectations: In [4], Fig. 23, the phase goes from -5 to +6 degrees, that is 11 RF degrees pk-pk, with head and tail of batch most affected. The bunch intensity considered in [4] is 21% higher than the present measurements (2.3×10^{11} ppb vs. 1.9×10^{11} ppb) but the voltage is also 25% higher (10 MV vs 8 MV). We conclude that the 2023 measurements agree well with the HL-LHC expectations in terms of expected beam quality at transfer to the LHC.

FEEDFORWARD

In normal operation the Cavity-Controller uses a tandem of One-Turn Delay Feedback (OTFB) and FeedForward [3].

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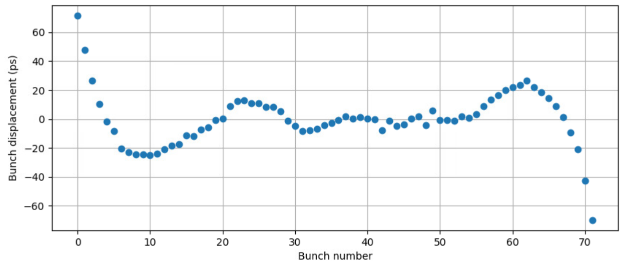

Figure 3: Bunch position offset along the batch.

Figure 4 shows the uncompensated beam loading in C1 with OTFB only: Comparing to Fig. 1 we see that the uncompensated beam loading now peaks at 150 kV and 200 kV at head and tail of batch respectively, to be compared to 130 kV and 120 kV with FeedForward ON. In the core of the batch the error reaches 60 kV, in good agreement with the OTFB gain (20 linear, from 1.16 MV to 60 kV). It was below 20 kV on Fig. 1. This will result in larger deviation in bunch position: With FeedForward OFF on ALL cavities we observe 200 ps pk-pk (14 RF degrees) to be compared to 10 RF degrees with complete regulation.

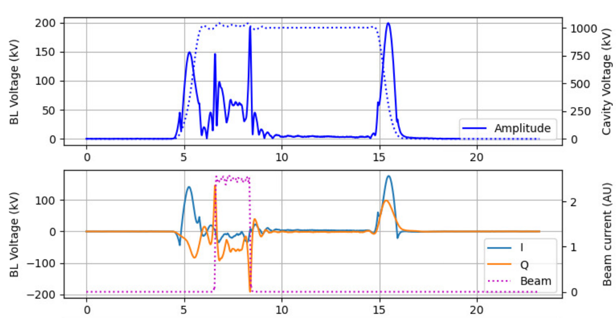

Figure 4: Uncompensated beam loading amplitude (top) and I,Q (bottom). Three-sections cavity (C1). Feedforward Off.

DRIVE LIMITING

Simulations showed that the LLRF drive (input to the power amplifier) would exceed the amplifier peak power for a short time, mainly at the edges of the batch [4]. To avoid this the LLRF drive is clamped at an adjustable level, before the output ADC [3]. During the test, C4 was the only cavity that reached the clamping level at 450 GeV/c. The bottom plot of Fig. 5 shows the LLRF drive and the amplifier power. When the drive (blue trace) would result in a power exceeding 650 kW (clamping level set in the test), it is saturating. The saturation lasts for a short duration and does not significantly impact the performance in terms of beam loading compensation. This clamping level will be increased to 1 MW and 1.6 MW, for the 3-section and 4-section cavities respectively, as the High Power Hardware is brought to nominal performance. This feature must be monitored carefully as the required amplifier power increases: The introduction of a saturating characteristic in a feedback can have undesirable effects. So far it works as in the simulations.

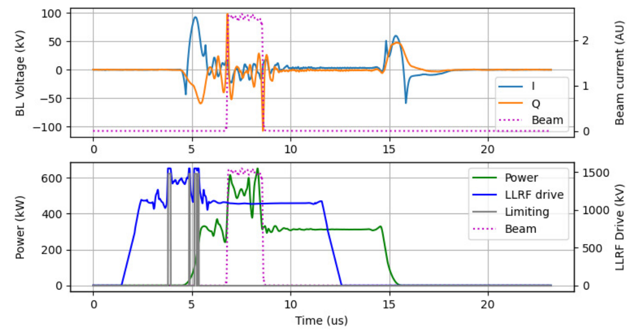

Figure 5: Uncompensated beam loading I,Q (top). LLRF drive and amplifier power (bottom). Three-sections cavity (C4).

CONCLUSIONS

The test data are very re-assuring on beam quality: All bunches are below the 1.6 ns length, and ten RF degrees pk-pk modulation along the batch, very close to the expectations [4]. The test was conducted with a bunch intensity (1.9×10^{11} ppb) lower than the HL-LHC (2.3×10^{11} ppb), but also with a lower voltage (8 MV compared to 10 MV). We can therefore anticipate that an $\approx$ 10 RF degrees spread will also be measured with the final intensity and voltage. The beam loading compensation fulfills the expectations: Factor 50 (linear) reduction in the core of the batch, factor 10 reduction in the first and last populated buckets. The power required is re-assuring for the 3-sections cavities: We observe overshoot reaching 620 kW, that is 22% above the 510 kW average, a bit less than the simulations (33%). The situation is less promising with the 4-sections cavities. The 1260 kW peak power with 1.9×10^{11} ppb is much higher than the simulations. Scaling this result to the HL-LHC conditions will exceed the 1.6 MW available from the power amplifier. The amplifiers powering these two cavities are new and their frequency response was not known when we ran the simulations. Instead we used a model identical to the old amplifier. The response was measured in late 2022. It is much broader band, resulting in a feedback response more aggressive than simulated. This must be tuned by reducing the Passband of the OTFB filter [4], before increasing the beam current significantly above 1.9×10^{11} ppb. The test was performed with one batch only. The HL-LHC beam calls for four such batches spaced by 225 ns gaps. The amplifiers must then deliver the beam-segment power during 8 μs.

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