

REMOVING KNOWN SPS INTENSITY LIMITATIONS FOR HIGH LUMINOSITY LHC GOALS

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Abstract

In preparation of the SPS as an LHC injector its impedance was significantly reduced in 1999 - 2000. A new SPS impedance reduction campaign is planned now for the High Luminosity (HL)-LHC project, which requires bunch intensities twice as high as the nominal one. One of the known intensity limitations is a longitudinal multi-bunch instability with a threshold 3 times below this operational intensity. The instability is presently cured using the 4th harmonic RF system and controlled emittance blow-up, but reaching the HL-LHC parameters cannot be assured without improving the machine impedance. Recently the impedance sources responsible for this instability were identified and implementation of their shielding and damping is foreseen during the next long shutdown (2019 - 2020) in synergy with two other important upgrades: amorphous carbon coating of (part of) the vacuum chamber against the e-cloud effect and rearrangement of the 200 MHz RF system. In this paper the strategy of impedance reduction is presented together with beam intensity achievable after its realisation. The potential effect of other proposals on remaining limitations is also considered.

KNOWN SPS INTENSITY LIMITATIONS

The nominal bunches with intensity of 1.15×10^{11} p/b spaced at 25 ns have been used since 2015 for physics in the LHC. In future, beams with intensity up to 2.4×10^{11} p/b will be required by the HL-LHC project and the LIU (LHC Injector Upgrade) project [1] is responsible for preparation of this beam. The SPS ring is the last accelerator in the LHC injector chain. Various upgrades were launched by the LIU project to remove known intensity limitations in the SPS which include e-cloud effect, beam loading and longitudinal instabilities. The upgrade of other SPS devices is also planned so that these high intensity beams are safely injected, extracted and transferred to LHC [1].

Presently the bunch intensity of 4 batches with 72 bunches spaced at 25 ns is limited to $\sim 1.4 \times 10^{11}$ p/b since relative beam losses are increasing with bunch intensities, reaching 20% for 1.7×10^{11} p/b injected. Possible reasons are e-cloud and beam-loading effects.

At the moment, acceleration of the LHC beam with emittance of 0.4 eVs (defined by injector) with an intensity of 1.3×10^{11} p/b requires higher RF power per 200 MHz cavity than the available 700 kW. The situation is similar on the SPS flat top, where short bunches are needed for clean injection into the bucket provided by the LHC 400 MHz RF system. The maximum bunch length allowed for extraction is established to be 1.9 ns with an average value of

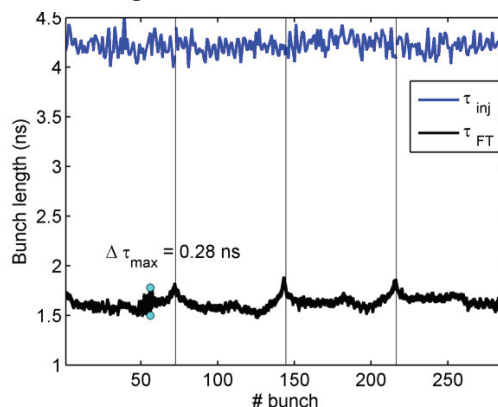


Figure 1: Bunch length (4σ Gaussian fit) measured for 4 batches with 72 bunches at injection (upper trace) and on the SPS flat top (lower trace) in double RF system. Average bunch length 1.65 ns and intensity 1.35×10^{11} p/b.

1.7 ns, see example in Fig. 1. In the present SPS RF configuration (two 4-section and two 5-section cavities) the available RF voltage falls quickly with increased beam intensity, however the RF upgrade (6 cavities with a total of 20 sections, two additional RF power plants of 1.6 MW and four existing ones upgraded to 1.05 MW) should increase the voltage available for HL-LHC intensity to 10 MV [2], see Fig. 2. Nevertheless, due to longitudinal instability leading to emittance increase during the ramp as well as due to induced voltage (potential well distortion, PWD), the voltage required on the SPS flat top is also increasing with intensity; an estimation from analytical scaling (red line) gives 12 MV. So far this instability is cured by the 800 MHz RF system operating in the Bunch Shortening (BS) mode and controlled emittance blow-up, but to achieve beam parameters required by the HL-LHC, the SPS impedance reduction had to be included in the LIU baseline.

IMPEDANCE REDUCTION

The main impedance sources responsible for longitudinal multi-bunch instabilities were recently identified to be vacuum flanges (VF) [3, 4]. There are nine main types of flanges in the SPS and they can be divided into two large groups (with approximately 400 and 240 flanges each) by the shape of the main adjacent vacuum chambers (QD or QF). The present plan is to shield 240 QF-type vacuum flanges which have resonant impedances with the highest R/Q. The implementation will start during the end-of-year stops (in one or two SPS sextants, most critical for future co-activities) and will be completed in the long shutdown 2

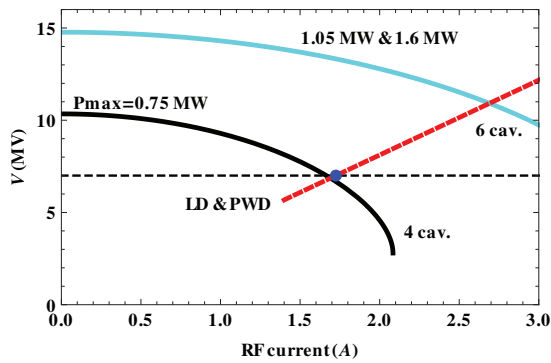


Figure 2: The 200 MHz voltage available at SPS flat top for different RF current in the present situation (black curve) and after RF upgrade (cyan) together with voltage required due to intensity effects (red). The 3.0 A RF current corresponds to 25 ns beam with 2.4×10^{11} p/b.

(2019-2020). To minimise vacuum interventions this will be done in synergy with a partial amorphous carbon coating against the e-cloud effect [1]. The majority of SPS flanges are insulating (enamel coating) with adjacent bellows and exact mechanical solutions for shielding are under study.

The instability thresholds found from particle simulations [5] for a realistic SPS impedance model and impedance reduction of the QF-type flanges [6] are shown in Fig. 3 for the situation before and after RF upgrade. For main resonant peaks of 131 insulating QF-flanges a reduction of R/Q by at least a factor 20 was assumed [4]. After shielding, the impedance of 27 non-insulating flanges and of 17 pumping ports was assumed to be zero. Reducing the quality factor Q of the 630 MHz HOM in the 200 MHz RF system by a factor of 3 could further increase the instability threshold (Fig. 3). However their damping is already very good and it is difficult to improve it significantly.

OTHER MEANS TO IMPROVE THE SPS PERFORMANCE

The simulation results presented in Fig. 3 are based on many assumptions and one of them is an accurate SPS impedance model. Indeed good agreement exists between simulations and measurements for single bunch stability during ramp in a single RF [7]. However measurements of the synchrotron frequency shift with intensity for different bunch lengths indicate that an effective inductive impedance $\text{Im}Z/n$ up to 1 Ohm could be still missing in the model [7]. In this case the instability thresholds are below the estimated values and additional measures, discussed below, could be useful to reach the HL-LHC goal.

Bunch rotation in the longitudinal phase space can be used to shorten too long SPS bunches just before their extraction to LHC. In simulations the length of bunches with 0.7 eVs emittance could be reduced from 2.2 ns to 1.55 ns after non-adiabatic voltage increase from 5 to 10 MV [8]. When tested in the SPS with 72 bunches, this method was

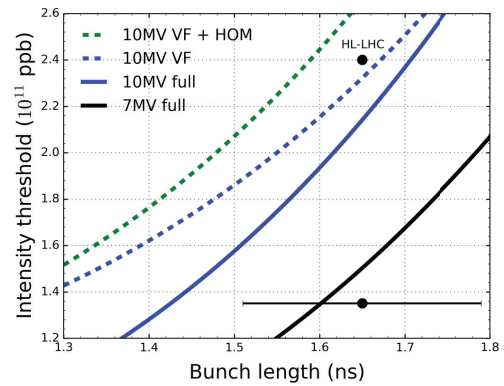


Figure 3: Instability threshold on the SPS flat top as a function of bunch length defined from particle simulations with 72 bunches for present RF system with 7 MV (black curve) and after upgrade with 10 MV (blue curve). Dashed blue curve shows results of impedance reduction of the QF-flanges and the green one with 630 MHz HOM damping in addition. Double RF (BS-mode) with 10% voltage at 800 MHz. Black circle shows measurements from Fig. 1.

limited by longitudinal instability (see example in Fig. 4), but still gave 20% shorter bunches than adiabatic voltage increase (1.3 ns versus 1.55 ns). Simulations confirm that on SPS flat top bunches with the same longitudinal emittance are more unstable in lower 200 MHz RF voltage, but after impedance reduction the instability threshold for 5 MV should be sufficiently high.

In 2016 it will be possible to have twice higher 800 MHz RF voltage than at the moment, thanks to operation of the 2nd cavity and RF power upgrade. With 150 kW at the cavity input up to 1.5 MV should be available for HL-LHC intensity. This increase of 800 MHz voltage should give another margin in beam stability as shown in Fig. 5. These optimistic results obtained on the SPS flat top should be

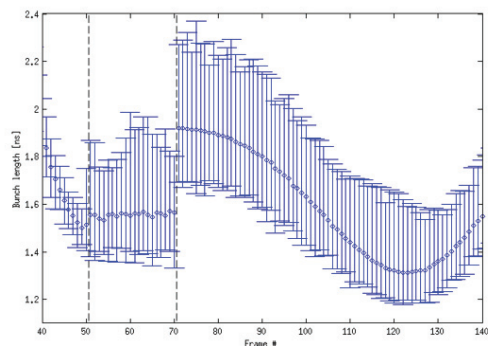


Figure 4: Average bunch length on the SPS flat top after the 200 MHz voltage increase from 3 MV to 7 MV in adiabatic (first part between dashed lines) and non-adiabatic (last part with bunch length oscillation) way. Measurements with 72 bunches with intensity of 1.1×10^{11} p/b.

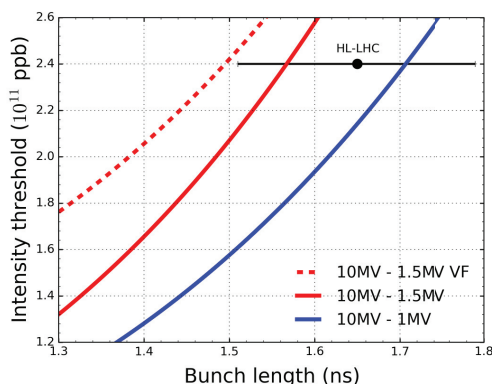


Figure 5: Instability threshold on the SPS flat top as a function of bunch length from particle simulations with 72 bunches in double RF (BS mode) for voltages of 10 MV at 200 MHz and 1 MV (blue line) or 1.5 MV (red line) at 800 MHz after RF upgrade. Red dashed line corresponds to the last case, but with VF impedance reduction.

still verified by particle simulations during the ramp. Note also bunch length variation (mainly due to controlled emittance blow-up in presence of beam loading), also visible in Fig. 1, and the fact that the shortest bunches are usually become unstable first, but particle loss in LHC is defined by the longest ones.

There are plans to study injection of longer bunches into the LHC (tolerable beam losses). The new 200 MHz RF system in the LHC would further relax the requirements on the SPS bunch length. However, the intensity limitations during the ramp should also be taken into account.

Even after the RF upgrade only intensities up to $2.4 \times$

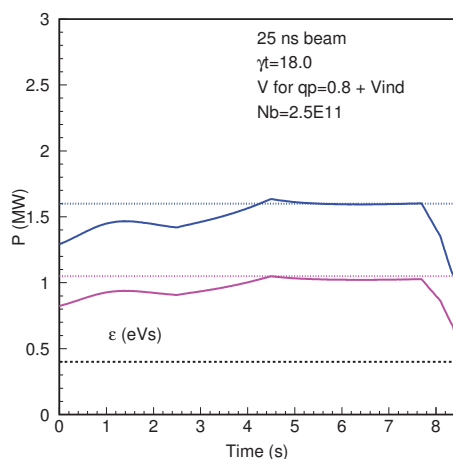


Figure 6: Power per SPS 200 MHz RF cavity having 3 (red curve) or 4 (blue) sections for 2.5×10^{11} p/b during the LHC cycle with voltage program for the constant filling factor in momentum (0.8) for emittance of 0.4 eVs, Induced voltage (for inductive impedance $\text{Im}Z/n=3.5$ Ohm and parabolic bunch) is taken into account in voltage program. Dashed lines show power limits after RF upgrade.

10^{11} can be accelerated in the SPS (no emittance blow-up during ramp), see Fig. 6. The optics with an intermediate transition gamma (between the present $\gamma_t = 18$ and previous $\gamma_t = 22.8$) would help to reduce the 200 MHz voltage and therefore power requirements during the ramp. A longer ramp could be another option to slightly relax power requirements [8], which was already tested in the SPS during preparation of high intensity doublet bunches for LHC scrubbing. These tests have uncovered a limitation due to slow transverse instabilities, which normally have no time to develop during nominal cycles.

SUMMARY

Possible ways of reaching longitudinal beam parameters required by the HL-LHC at extraction from the SPS have been considered. They include increased RF voltage in both 200 MHz and 800 MHz RF systems, a new campaign of longitudinal impedance reduction (in particular, shielding of the vacuum flanges), beam manipulations (bunch rotation) on the SPS flat top and new SPS optics. Other potential intensity limitations in SPS (as e.g. from interception devices and e-cloud effect) also exist, but were not considered here.

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