OTHER MEANS TO INCREASE THE SPS 25 ns PERFORMANCE - LONGITUDINAL PLANE

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Abstract

At the end of the LHC run 2 in 2012 the 25 ns beam with an intensity of 1.3×10^{11} p/b was successfully accelerated in the SPS. Further significant increase of bunch intensity in the SPS requires that all LIU baseline upgrades are in place (for 200 MHz and 800 MHz RF systems and e-cloud mitigation), but even then the bunch intensity could be limited below the HL-LHC value of 2.5×10^{11} by beam-loading and longitudinal beam instabilities. In this paper other means to increase the 25 ns beam performance are considered. In particular, we study the potential gain in stability for bunches with larger longitudinal emittance at the SPS extraction, possible in the scenario with a 200 MHz RF system in the LHC. The expected longitudinal limitations (coupled-bunch instability, loss of Landau damping, microwave instability and RF power during the ramp) are analyzed for a single and double RF operation and different optics (Q20, Q26 and intermediate one). Bunch rotation before extraction to the LHC is also addressed as a potential technique to decrease capture losses of long bunches in the LHC.

STATUS BEFORE LS1

The nominal LHC beam with 25 ns spacing was used in the LHC for scrubbing against the e-cloud. Measurements with high intensity 25 ns LHC beam were performed in the SPS during a few machine development (MD) sessions at the end of 2012 (before the long shutdown 1, LS1). As a result 4 batches with an intensity of 1.35×10^{11} p/b and an average bunch length $\tau_{4\sigma} \approx 1.7$ ns were successfully accelerated to the SPS flat top [1]. However, during these MDs high beam losses (>10%) were observed for injected intensities more than 1.4×10^{11} p/b, as shown in Fig. 1. Note that to reduce losses it was necessary to program the 200 MHz RF voltage amplitude to the maximum available value of 7 MV, defined by the beam-loading effect. In addition, for these intensities longitudinal beam instabilities were also observed during the ramp or at the flat top.

PERFORMANCE LIMITATIONS FOR THE HL-LHC PARAMETERS

According to the HL-LHC project [2], beams with an intensity up to 2.4×10^{11} p/b will be requested from the SPS. This means that one needs to almost double the bunch intensity N_b in the SPS while maintaining the same bunch length at extraction ($\tau_{4\sigma} \leq 1.7$ ns), restricted by the LHC 400 MHz RF system. At the moment $\tau = 1.9$ ns is the maximum bunch length (even for a single bunch) allowed by the Beam Quality Monitor (BQM) [3] for injection into the LHC. However, for higher intensities, larger longitudinal emittance ε_l is needed for longitudinal beam stability in the SPS. To avoid loss of Landau damping during acceleration (single bunch effect) the emittance should be increased according to the scaling $\varepsilon_l \propto N_b^{1/2}$ and that will require a higher RF voltage than used now. However, due to the effects of beam-loading and potential-well distortion a limitation to the available RF voltage exists now and is still expected in future, after the RF upgrade (but at the different level).

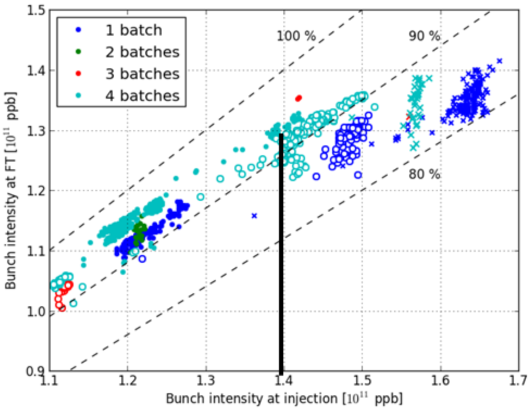

Figure 1: Bunch intensity at the SPS flat top versus the intensity at injection. The black vertical line indicates the point above which the intensity on the flat top doesn't increase anymore and the losses become larger than 10%.

RF Voltage Limitation

The calculated available RF voltage at the SPS flat top is shown in Fig. 2 for the present situation (2 cavities of 2 sections and 2 cavities of 5 sections, black curve) and after the upgrade of the 200 MHz RF system [4] (cyan curve), when more 200 MHz RF cavities will be installed with two additional RF power plants (2 cavities of 4 sections with 1.6 MW maximum power at cavity input and 4 cavities of 3 sections with 1.05 MW). The upgrade of the low level RF (LLRF) will allow operation in the pulsing mode at revolution frequency, using the fact that the LHC beam occupies less than half of the SPS ring.

Starting from the reference point, defined by the latest experimental achievement (point in Fig. 2 at ~1.7 A with N_b $\sim1.35\times10^{11}$ p/b and $\tau_{4\sigma} = 1.7$ ns) and assuming constant bunch length at the SPS extraction, the minimum emittance (and therefore voltage) needed for beam stability (avoiding possible loss of Landau damping) can be calculated. Moreover, for this calculation the RF voltage reduc-

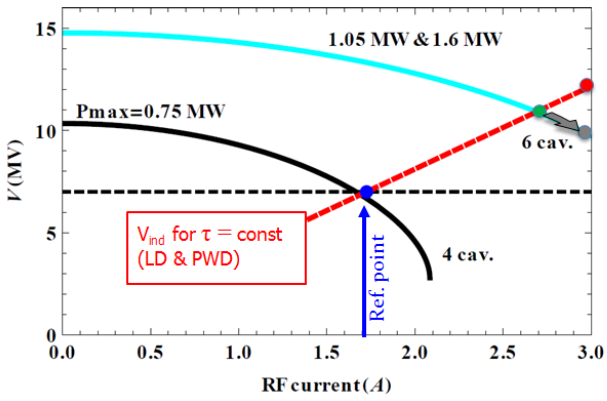

Figure 2: Voltage in the 200 MHz RF system available at the SPS flat top as a function of the RF current. The RF current of 1.47 A corresponds to the 25 ns beam with nominal bunch intensity. The black curve corresponds to the present situation and the cyan curve to the situation after the upgrade of the 200 MHz RF system (in 2020) [4].

tion due to voltage induced in the reactive part of the SPS impedance, $\mathrm{ImZ/n} = 3.5\ \Omega$, (effect called potential-well distortion) was also taken into account. From the intersection of the two curves for the needed and the available voltage after the 200 MHz RF system upgrade, an intensity of around 2.7 A (2.1×10^{11} p/b) can be reached without performance degradation. For higher bunch intensity (3 A or 2.3×10^{11} p/b) only 10 MV will be provided, while 12.5 MV are required for beam stability. Therefore, some additional measures should be taken in order to satisfy the HL-LHC needs. This can be achieved either by reducing the uncontrolled emittance blow-up observed in the SPS or by increasing the limit for the longitudinal emittance acceptable on the SPS flat top. These options are analyzed below in more detail.

Uncontrolled Emittance Blow-up

Longitudinal emittance blow-up is observed in the SPS for both single and multi-bunch beams pointing out that some high frequency resonant impedance could be responsible for this effect. To identify the guilty impedance, measurements with very long bunches ($\tau \approx 25$ ns) and RF off were performed at the SPS flat bottom and a strong peak at frequency around 1.4 GHz was observed [5]. An example of these measurements is presented in Fig. 3.

As has been found later this resonant peak originates from the impedance of certain SPS vacuum flanges [6]. Several types of these flanges are used for the connection of various machine elements and their total number in the ring is around 500.

Macro particle simulations based on the SPS impedance model which includes RF cavities, resistive wall, injection and extraction kickers [7], as well as the impedance of the vacuum flanges were performed in order to compare their results with different measurements, both for single- and multi-bunch beams. An example for single high intensity bunches with the Q20 optics and a double RF system (bunch shortening mode) is shown in Fig. 4, where bunch lengths found from simulations and measurements at the SPS flat top are plotted together.

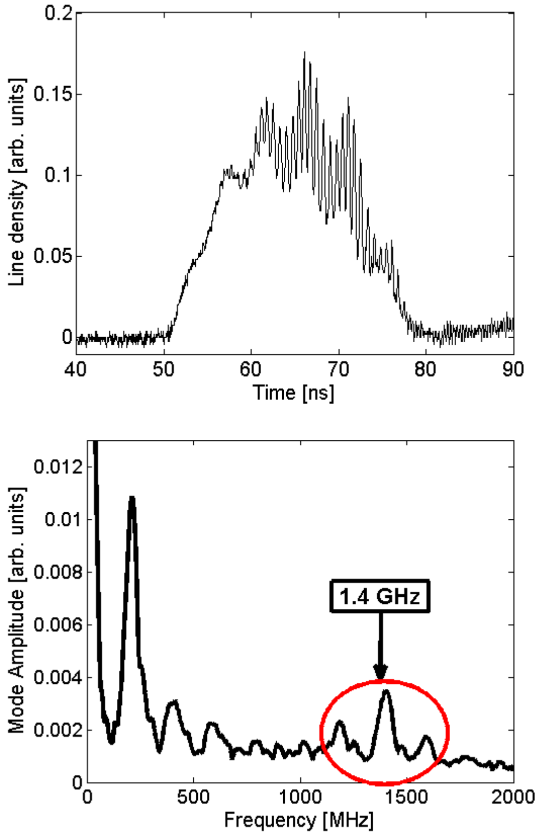

Figure 3: Example of measurements performed on the SPS flat bottom with long bunches ($\tau \approx 25$ ns) and RF off [5]. Top: bunch profile modulated at 200 MHz and a higher frequency ($\sim$ 1.4 GHz). Bottom: projection of the Fourier spectra of all the bunch profiles acquired during $\sim$ 100 ms. Measurements in the Q26 optics with bunch intensity $\sim 1 \times 10^{11}$.

The results are in good agreement since both in measurements and simulations a strong increase of the bunch length with intensity is observed. This increase can not be attributed to the potential well distortion. Therefore, a blow-up of the bunch must have occurred during the cycle, pointing to a microwave type of instability due to a high frequency resonant impedance. In simulations there is a clear instability threshold at $N_{\mathrm{th}} = 2 \times 10^{11}$ p, not visible from these measurements. Note that in these measurements the 200 MHz voltage was very low (2 MV), which is good for Landau damping but unfavorable for microwave instability. The main contribution to this uncontrolled blow-up is coming from the resonant impedance of the vacuum flanges. Indeed, simulations show that without the vacuum flanges the instability threshold is twice higher ($N_{\mathrm{th}} \sim 4\times10^{11}$ p).

Simulations were also carried out with a multi-bunch beam at the SPS flat top. At the moment only six bunches

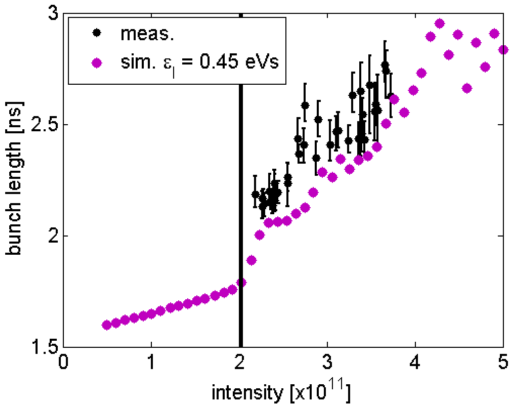

Figure 4: Measured and simulated bunch length as a function of intensity for a single bunch at the SPS flat top in the Q20 optics and a double RF system (bunch shortening mode). The voltage at 200 MHz was $V_{200} = 2$ MV and at 800 MHz $V_{800} = 200$ kV.

(spaced by 25 ns) could be simulated and thus only qualitative conclusions can be drawn. For the same longitudinal emittance the instability threshold for 6 bunches has been found to be almost twice lower than that for a single bunch. This result, presented in Fig. 5, is in agreement with measurements in a double RF system (200 MHz and 800 MHz), where the single bunch instability threshold is approximately twice higher than the multi-bunch one.

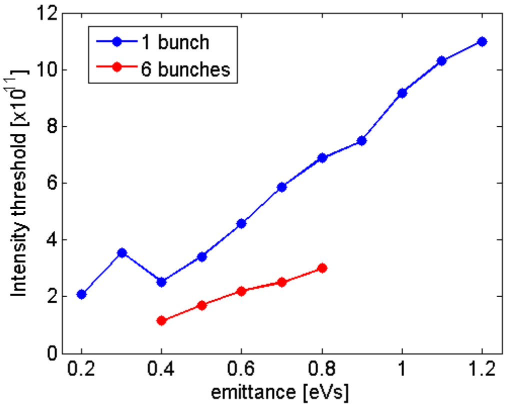

Figure 5: Instability threshold found in simulations for a single- and a 6-bunch beam at the SPS flat top in the Q20 optics and a double RF system (bunch shortening mode). The voltage at 200 MHz was $V_{200} = 7$ MV and at 800 MHz $V_{800} = 640$ kV.

In addition, in simulations only a coupling between a few bunches (3 or 4) was observed and no coupled-bunch mode could be identified, similar to all beam observations. Indeed, in measurements bunches spaced by 25 ns or 50 ns are coupled, but the distance of 225 ns between the PS batches is enough to practically fully decouple them (instability thresholds in the SPS with 1 or 4 batches are very similar). Finally, as expected and shown in Fig. 5, stability is higher for larger emittances, both for single and multi-bunch beams.

POSSIBLE MEANS TO INCREASE INTENSITY AT SPS EXTRACTION

For high bunch intensities required by the HL-LHC project, large longitudinal emittance ($\varepsilon_l > 0.6$ eVs) will be unavoidable at the SPS flat top either from controlled or uncontrolled emittance blow-up (due to beam instability). However, according to the present situation, this will lead to significant particle losses at beam transfer to the LHC. To overcome this limitation three solutions are considered below.

Bunch Rotation on the SPS Flat Top

Bunch length can be reduced by bunch rotation in the longitudinal phase space during a quarter of the synchrotron period. This rotation can be done after step-wise voltage increase and was already successfully tested on the SPS flat top during an MD in 2012 (for the AWAKE experiment) [8] with single, high intensity ($\sim 2.5 - 3 \times 10^{11}$ p) bunches. An example is presented in Fig. 6, where starting from $\tau_{4\sigma} \sim 2.2$ ns a bunch length of $\tau \sim 1.2$ ns was obtained.

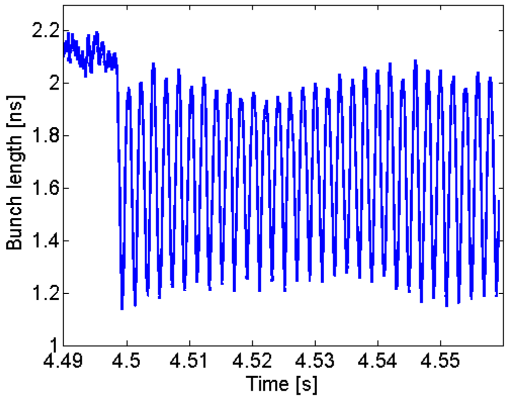

Figure 6: Example of measured synchrotron oscillations of a single bunch with intensity of 2.8×10^{11} on the SPS flat top after the 200 MHz RF voltage was increased from 2 MV to 7.5 MV [8].

However, during these measurements bunches with small emittances of ($\varepsilon_l \sim 0.3$ eVs) were used, while for the future LHC beam much larger values of the longitudinal emittance are needed (at least double). This means that much larger bunch tails can be expected, so that particle losses in the LHC may still remain an issue. In order to study this RF manipulation, particle simulations were performed for a full batch (72 bunches) both on the SPS flat top and the LHC flat bottom, using the SPS and LHC impedance models respectively. In particular, for the SPS case, a simplified model of the feed-back and feed-forward loops that are installed around the 200 MHz RF cavities, was also introduced. The results for a bunch by bunch position variation along the bunch, similar to the one found from measurements are shown in Fig. 7.

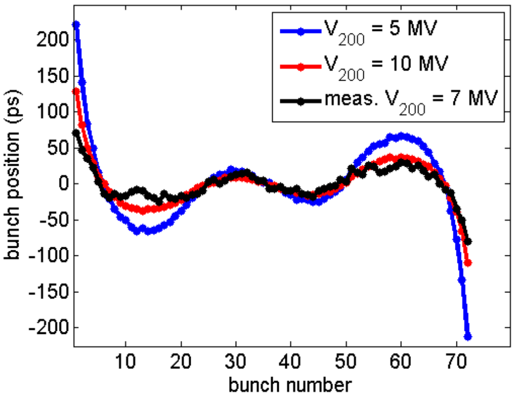

Figure 7: Measured (black curve) and simulated bunch by bunch position variation along the batch. In simulations the 200 MHz RF voltage was increased from 5 MV to 10 MV, intensity 2.4×10^{11} p/b. In measurements $V_{200} = 7$ MV and intensity 1.3×10^{11} p/b.

In the simulations the SPS voltage at 200 MHz was increased from 5 MV to 10 MV (will be available at flat top after the RF upgrade for intensities $\sim 2.3 \times 10^{11}$ p/b, see Fig. 2). Furthermore, a longitudinal emittance of $\varepsilon_l = 0.7$ eVs (required for single bunch stability from scaling discussed above) was used. The results are presented in Fig. 8, where starting from an average bunch length $\tau_{\text{mean}} = 2.2$ ns the beam ended with $\tau_{\text{mean}} = 1.56$ ns, acceptable for extraction to the LHC.

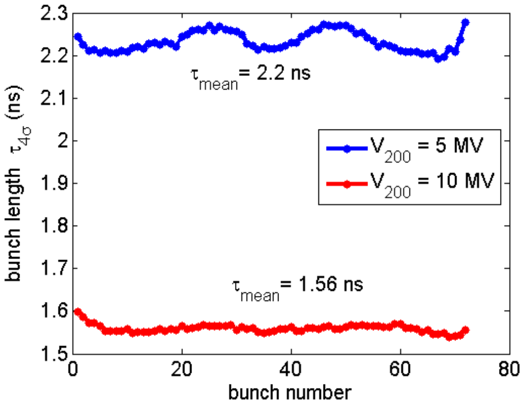

Figure 8: Bunch length along the batch before (blue) and after (red) rotation, obtained from particle simulations.

As a second step, in order to quantify the effect of bunch distribution and of the bunch position variation along the batch on the particle losses, these bunches were "injected" in simulations into the LHC and captured with an RF voltage of 8 MV at 400 MHz. Figure 9 presents examples of the LHC longitudinal phase space for bunches at the beginning, the middle and the end of the batch. It is clear from the figure that due to beam loading in the SPS, the bunches at the batch edges are shifted with respect to the bucket centers.

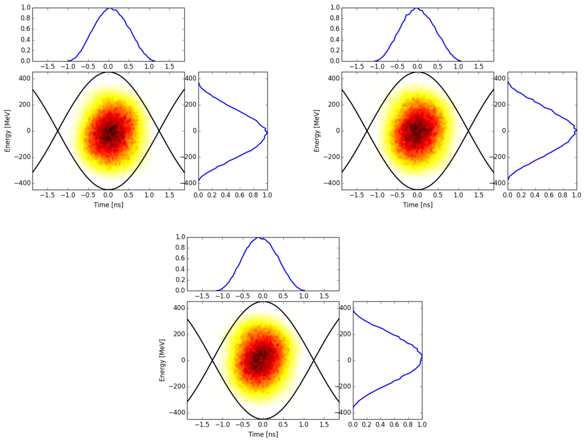

Figure 9: Bunches at different positions in the batch inside the LHC buckets (8 MV) after rotation on the SPS flat top: bunch 1 (top left), 36 (top right) and 72 (bottom). Bunches 1 and 72 are shifted with respect to the bucket center. Courtesy J. E. Müller.

The beam loss pattern along the batch obtained from tracking this beam in the LHC is shown in Fig. 10. As expected, for the bunches at the edges more losses are observed but they are less than 0.6%.

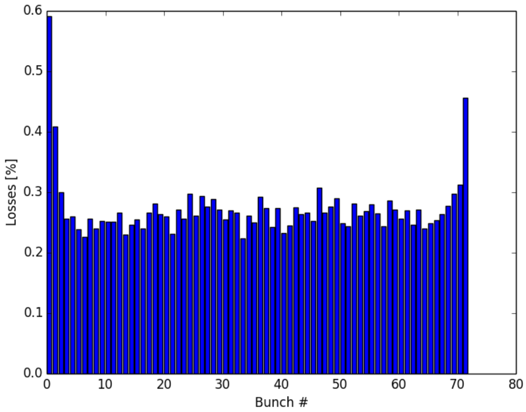

Figure 10: Beam loss pattern of the rotated batch (72 bunches) in the SPS after capture in the LHC. Courtesy J. E. Müller.

200 MHz RF System in the LHC

An alternative solution for increasing the acceptable longitudinal emittance at extraction from the SPS is an installation of the 200 MHz RF system in the LHC. The capture system based on the warm cavities was foreseen already in the LHC DR [9]. Recently a new super-conducting 200 MHz RF system was proposed [10]. This system of course will eliminate capture losses even for much longer SPS bunches. Furthermore, it will allow the operation in a double RF system with all the benefits that this entails (better longitudinal stability, e-cloud effects, flat bunches, etc.), but at the same time with all the complications that this can imply (phase control, maintenance, reliability issue, etc.). In addition, installing a new RF system in the LHC will lead to an increase of the beam impedance (for more information see [10, 11]).

Impedance Reduction in the SPS

Another solution is to decrease the emittance blow-up by reducing the longitudinal impedance of the SPS and thus increasing the longitudinal instability threshold. Great effort was made during the last 2 years to identify the responsible impedance sources by beam measurements and simulations [5, 12] as well as by electromagnetic simulations and measurements in the lab of the impedance of different devices in the SPS ring.

As aforementioned, the impedance spectrum of the SPS was measured with beam and a strong resonance at 1.4 GHz was found. A thorough, element-by-element, impedance assessment was then started to find the source of the 1.4 GHz resonance.

A subset of $\sim$ 120 vacuum flanges, all similar to the one shown in Fig. 11(a), has been found to resonate at 1.4 GHz. Electromagnetic simulations and RF measurements [13] were carried out to determine the impedance of these elements. For the whole subset, the R/Q contribution is $\sim$ 9 kΩ. In addition, the impedance of the other types of vacuum flanges has been also calculated. Significant resonances were found around 1.2, 1.8 and 2.5 GHz.

Overall, there are around 500 high-impedance vacuum flanges in the SPS ring. These vacuum flanges can be classified in the two main groups, with elliptical and circular beam pipes attached, hereafter groups I and II respectively. Group I is responsible for the 1.2 and 1.4 GHz resonances and group II for the higher frequency resonances (1.8 and 2.5 GHz).

Recently, several possibilities for impedance reduction of the vacuum flanges were studied. The different alternatives were narrowed down to the two most promising ones, namely, partial shielding and redesign of the flanges [14].

The impedance of the vacuum flanges from group I could be significantly reduced by partial shielding of the empty volume produced by the bellows, as shown in Fig. 11(b). This partial shielding can reduce the R/Q of the 1.4 GHz resonance by a factor from 8 to 12, depending on the implementation. On the one hand, this is a relatively cheap and easy to implement solution. On the other hand, only flanges from group I (roughly half of the total number of high-impedance flanges) could be acted upon.

The second possible alternative is to redesign the flanges and bellows to minimize their impedance. This solution implies manufacturing elliptical bellows and redesigning current circular ones. Initial studies show a factor 20 reduction for the R/Q of the 1.4 GHz resonance. In addition, the impedance of the flanges from group II could also be minimized. However, this is a more expensive solution, not only due to the cost of producing elliptical bellows but also because their installation involves cutting and welding.

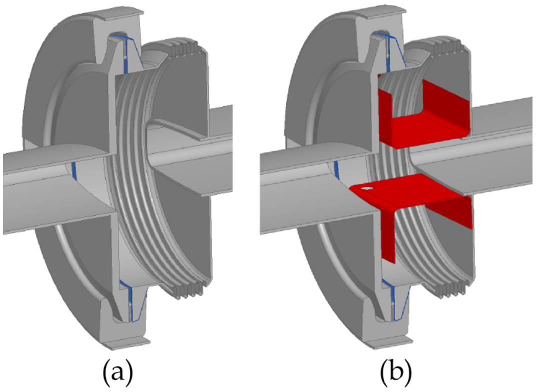

Figure 11: Model of a QF-MBA enamelled SPS vacuum flange, the source of a strong 1.4 GHz resonance (longitudinal cut). (a) Empty flange. (b) Possible implementation of the partial shielding (highlighted in red).

LIMITATIONS DURING THE ACCELERATION RAMP

Assuming that the restrictions for having large longitudinal emittance at the SPS flat top have been removed, the acceleration of these bunches should be also analyzed with respect to the limited RF power available in future.

Below, the necessary RF voltage during the cycle is calculated for a varying longitudinal emittance ε_l and a constant filing factor in momentum q_p. On flat bottom, ε_l is taken from measurements (0.4 eVs for the Q20 optics), while on flat top a larger value is required for beam stability, defined by the bunch intensity N_b. A controlled emittance blow-up should be applied from certain energy, which depends on the final emittance (N_b). For $N_b = 2.4 \times 10^{11}$ p/b the latter should be 0.7 eVs in the Q20 optics (scaled for single bunch stability). Concerning the filling factor, the value of $q_p = 0.75$ was assumed to provide some margin for beam losses. Note that for a similar filing factor in MDs of 2012, losses of more than 10% were observed (Fig. 1). In addition, the effect of the potential well distortion should be also taken into account. In particular, during cycle the induced voltage for a given bunch length and for $\mathrm{ImZ/n} = 3.5\ \Omega$ was calculated and added to the RF voltage.

For this total voltage, the required RF power can then be calculated for each type of RF cavity, assuming power partition proportional to the maximum available power. The RF power during the cycle is plotted in Fig. 12 for the present (2014) duration of the acceleration ramp (8.5 s) and intensity of 2.5×10^{11} p/b (assumed to take into account the $\sim$4% losses due to the beam scraping that is applied at the end of the ramp). As shown in the Fig. 12, even after the 200 MHz upgrade, the required RF power is well above the power limits both for 3- and 4-section cavities (horizontal dotted lines), making impossible the acceleration of this high intensity beam with the same ramp length.

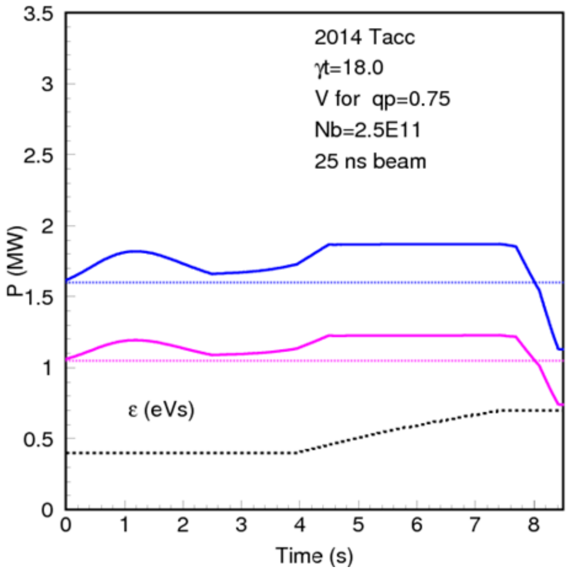

Figure 12: RF power in the Q20 optics required by 3- (magenta) and 4- (blue) section cavities, through the present (2014) acceleration cycle for intensity of 2.5×10^{11} p/b together with the corresponding power limits. A controlled emittance blow-up applied from $\varepsilon_l = 0.4$ eVs to 0.7 eVs (dotted black line). Voltage program calculated for $q_p = 0.75$.

A possible solution is to increase the duration of the SPS acceleration cycle and as shown in Fig.13, twice longer time compared to the 2012 SPS cycle is almost sufficient for acceleration of intensities required by the HL-LHC. The initial part, where higher power is needed can be possibly improved by redesigning the magnetic cycle.

Nevertheless, increasing the length of the SPS acceleration cycle will result in longer filling time of the LHC (30% more than in 2012 for dedicated filling) and will increase the average power consumption in the SPS. Furthermore, the bunches will stay longer in the SPS and this may give more time for instabilities to develop. First conclusions about the consequences of a longer SPS cycle can be deduced already this year, since a longer cycle is also necessary for acceleration of the doublets required for scrubbing of the LHC in 2015 [15].

NEW OPTICS

In case the RF power during the ramp is still an issue with the Q20 optics ($\gamma_t = 18$) one can consider increasing the transition energy (decreasing the slippage factor η). However, going back to the Q26 optics ($\gamma_t = 22.8$) is not an option due to beam stability issues at injection energy. Therefore, a compromise between the two options is an intermediate γ_t. In particular, as shown in [16] a possible solution is $\gamma_t = 20$ (Q22 optics).

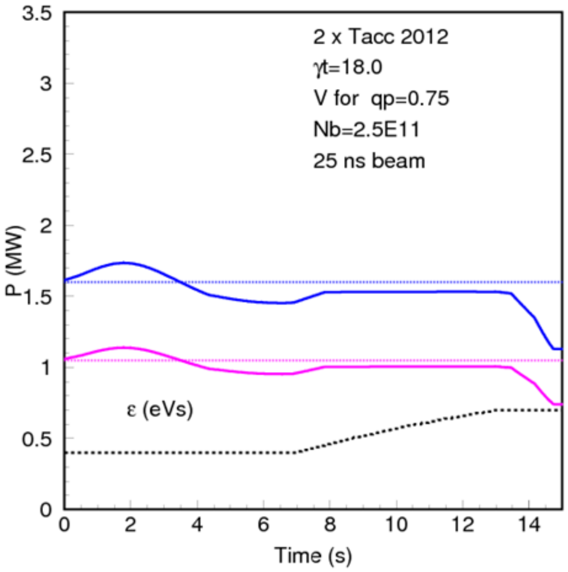

Figure 13: RF power required by 3- (magenta) and 4- (blue) section cavities, through a twice longer than the 2012 acceleration cycle. Similar conditions as in Fig. 12.

Initially, in order to study the beam stability with the Q22 optics, particle simulations with the SPS impedance model were performed for a single bunch at the flat top and for comparison the results are presented in Fig. 14 together with those for Q20 and Q26. As expected, from stability point of view the Q22 optics is practically between Q20 and Q26.

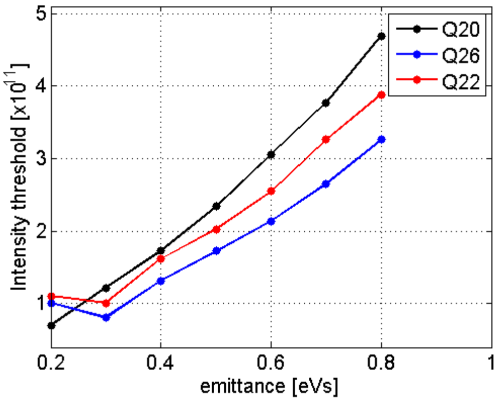

Figure 14: Instability threshold found in simulations for different SPS optics, for a single bunch at the SPS flat top in a double RF system (bunch shortening mode). The voltage at 200 MHz $V_{200} = 2$ MV and at 800 MHz $V_{800} = 200$ kV.

The power requirements during the acceleration cycle in the Q22 optics calculated for the intensity of 2.5×10^{11} p/b and a twice longer ramp (as in Fig. 13) are presented in Fig. 15. Note that even with these optics a longer cycle is still needed due to a strong beam loading, since a larger controlled emittance blow-up is necessary to be applied during the ramp to ensure beam stability. However, comparing with the Q20 optics (Fig. 13) one can see that the Q22 optics provides more margin in the RF power.

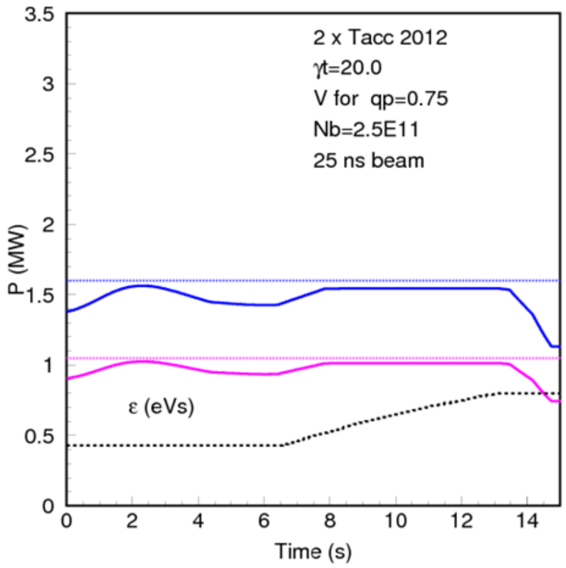

Figure 15: RF power in the Q22 optics required by 3- (magenta) and 4- (blue) section cavities through a twice longer than the acceleration cycle used in 2012. Controlled emittance blow-up applied from $\varepsilon_l = 0.425$ eVs to 0.8 eVs (dotted black line). Similar conditions as in Fig. 12.

CONCLUSIONS

The SPS intensity is limited by the available RF voltage (due to beam loading) and by the longitudinal emittance blow-up (due to instabilities). These limitations are coming from both the acceleration ramp (losses in the SPS) and the SPS-LHC transfer (LHC capture losses). For the 25 ns beam, the intensity limitation is now around 1.3×10^{11} p/b and is expected to become $\sim 2.0 \times 10^{11}$ p/b after the upgrade of the 200 MHz RF system. Possible measures to reach the intensities required by the HL-LHC (2.4×10^{11} p/b) were discussed. In particular, doubling the duration of the acceleration ramp will allow the acceleration of the large emittances, needed for beam stability. Later in the cycle, at top energy, it would be possible to transfer these long bunches into the LHC either by performing a bunch rotation in the SPS or by installing a new SC 200 MHz RF system in the LHC. On the other hand, the uncontrolled emittance blow-up can be avoided by reducing the responsible impedance sources. This, most robust solution, will improve the situation both during the SPS ramp and on the flat top, but first these impedance sources should be definitely identified. Finally, it was shown that the Q22 optics will provide additional flexibility between the Q20 and Q26 optics, but the Q20 is still considered as the main option for Run 2.

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