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Estimated LHC RF system performance reach at injection during Run III and beyond

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Summary

This note describes the performance limitations of the present LHC RF system on the injection plateau, in view of increased intensities in Run III and in the HL-LHC era. The minimum required injection voltage is derived from beam dynamics constraints and operational experience. The maximum available voltage is given by beam measurements with the half-detuning beam-loading compensation scheme. From these two constraints, the performance reach with increased intensities is evaluated. Various studies, such as a potential RF upgrade, or alternative beam-loading compensation scenarios, are recommended.

Contents

1 Introduction

In the preliminary baseline for the HL-LHC project, no upgrade of the main RF system was foreseen, although higher- and lower-harmonic systems were studied for beam stabilisation, the transfer of larger emittances from the SPS, and emittance growth on flat bottom due to IBS [1]. The theoretical average power consumption in the half-detuning scheme [2] is between 200 kW to 275 kW, with 6 MV to 8 MV total voltage per beam, respectively, for the HL-LHC target intensity of 2.3×10^{11} ppb. According to its design value of 300 kW/klystron, the present RF system should in principle not be limited in power at injection. For the energy ramp and flat top, the full-detuning beam-loading compensation scheme [3] has been used operationally since 2017 [4].

Operational experience, however, shows that the present RF system is more limited in power than previously assumed. Power transients between beam- and no-beam-segments have to be included in the analysis. This note evaluates the operational limits and the future performance reach of the system.

To evaluate the power consumption, an important ingredient is what injection voltage is required in the LHC. In the LHC design report [5], 8 MV was originally suggested without operational experience. With the first batched beams of 72 bunches and more, produced in the standard 25 ns production scheme and with Q26 optics in the SPS, the injection voltage was optimised to 6 MV, to reduce injection oscillations while keeping low capture losses. When the Q20 optics was deployed in operation in the SPS, the LHC injection voltage could have been reduced to 4.7 MV with the same beam; this was not done as the performance in the LHC was not deteriorated due to the higher voltage. Using then BCMS-type beam instead of the nominal 25 ns beam, which reduces the average bunch length at extraction from 1.65 ns to 1.50-1.55 ns, the required voltage in the LHC scales down further to about 3.9-4.2 MV.

Once the BCMS beam with the Q20 optics in the SPS was used in the LHC, strong injection oscillations were observed [6], originally initiating the recent voltage reduction campaign [7]. As presented here, the lower voltage is also required to minimise the power consumption of the RF system with increased intensities in the future.

2 Limitations known from present LHC operation

In order to study the performance reach of the LHC RF system at injection, two ingredients are needed: (i) the minimum voltage necessary from the beam loss point of view, allowing for operation without beam dumps due to losses, and (ii) the maximum voltage achievable in the system with beam and with operational margin avoiding cavity trips. In the following, we summarise the operational experience concerning these two points, and estimate the future performance based on this experience.

2.1 Minimum injection voltage

During most of Run I and Run II, the operational RF voltage at injection was 6 MV total per beam. Originally, this working point was chosen to reduce capture and flat bottom losses for beams produced in the SPS in the Q26 optics, with the 25 ns standard beam production scheme. Today, this voltage is not optimal anymore, since the BCMS-type beam produced in the Q20 optics is both shorter in bunch length and smaller in momentum spread. As a result, strong oscillations have been observed in beam measurements. The optimum injection voltage in the LHC is a trade-off between reducing losses that calls for an increased voltage and minimising injection oscillations and power consumption, which both call for a decreased voltage. Recent studies [6] suggested to use 4 MV as the new working point for BCMS beams, which is in line with the scaling considerations presented in the Introduction. As a result, a voltage reduction campaign [7] has been performed in August this year, decreasing the RF voltage from 6 MV to 4 MV in steps of 0.5 MV over a period of three weeks.

The 4 MV total voltage results in general in better-matched bunches and reduced injection oscillations when the injection error is small. The power consumption is reduced as well. On the other hand, due to the reduced bucket area, capture and start-of-ramp losses increase. Figure 1 shows the average, 4-sigma equivalent FWHM bunch length per beam at the start of the ramp for different fills in the voltage reduction period.

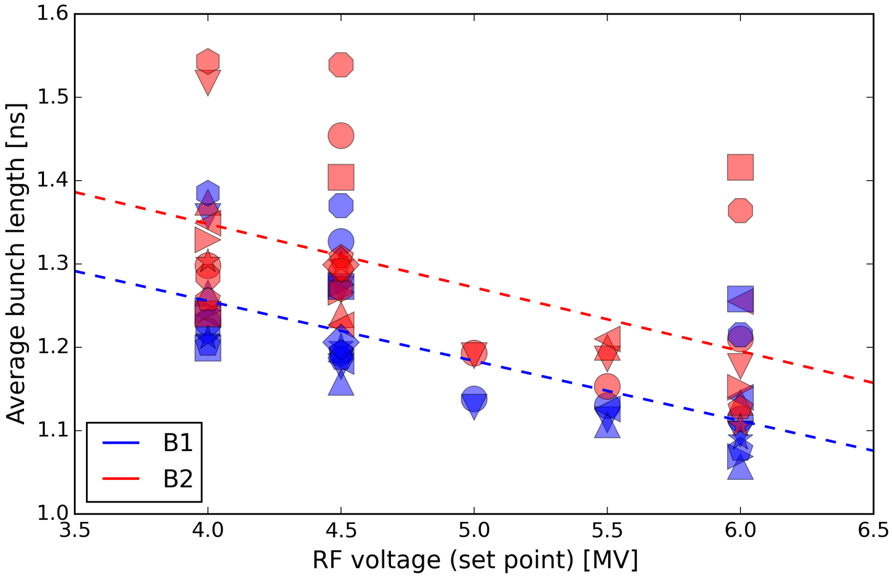

Figure 1: Average bunch length in B1 (blue) and B2 (red) as a function of total injection voltage, at the start of the ramp. Fills 7035 through 7105 and fills 7135, 7137, 7139. The average bunch length increases in B1 from 1.11 ns to 1.25 ns and in B2 from 1.20 ns to 1.35 ns by reducing the voltage from 6 MV to 4 MV.

The average bunch length scales with voltage as expected from scaling laws; i.e. the corresponding emittance is preserved. Beam 2 is globally longer than Beam 1, which is attributed to worse energy matching in general. From time to time, however, the beam is blown up right after injection, resulting in bunch lengths from 1.4 ns to 1.6 ns. This blow-up is attributed to fluctuations of the energy mismatch between the SPS and the LHC; in the tomographic reconstruction of the longitudinal phase-space distribution at injection of fills 7135, 7137, and 7139, the mismatch was observed to be up to 50-60 MeV on both beams. An example is shown in Fig. 2.

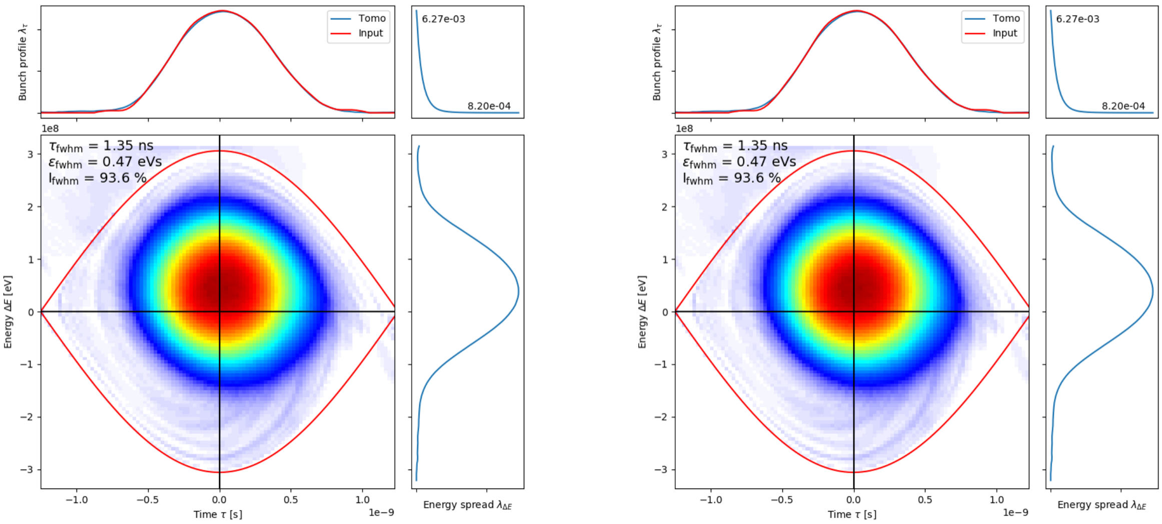

Figure 2: Tomographic reconstruction of two bunches at injection in B1 (left) and B2 (right). First turns at injection in Fill 7137. The energy mismatch of 50-60 MV causes blow-up in both beams. Courtesy of T. Argyropoulos.

This significant energy error between the SPS and the LHC occurs only from time to time, and is more difficult to digest with lower injection voltage, as the bucket area is smaller and more halo particles leak out causing losses. Indeed, with the 4 MV injection voltage and injection errors, beam losses of up to 80 % of the dump threshold have been observed at the start of the ramp for such fills. Nevertheless, no dumps due to the lowered RF voltage have occurred yet, but there is virtually no margin left to lower the voltage further.

Thus, the RF voltage has to be large enough to accommodate energy and phase errors. Phase errors are corrected by the operators on a fill-by-fill basis and they usually do not exceed 5-10°. In comparison, the energy error of 50 MeV translates to a phase error of 30°. Although the beam phase loop can correct the injection errors for the first batch, subsequent batches are corrected less and less as the phase loop averages over all bunches in the machine. With typically 20 injections per beam, the injection errors are on average practically not corrected, and circulating bunches are even kicked at each injection.

To avoid beam dumps due to losses at or after injection, and thus decreased machine performance, the injection voltage can be increased to have more operational margin. Alternatively, a longitudinal damper could be implemented to damp the injection errors bunch-by-bunch and thereby reduce the beam losses. Having a longitudinal damper in the future would be preferential, and would give some operational margin. However, even with a longitudinal damper, it is not recommended to decrease the injection voltage further, as eventually significant capture losses are expected to occur [6].

In conclusion, the 4 MV injection voltage used presently is the absolute minimum working point with the BCMS beam arriving on average with about 1.50-1.55 ns 4-sigma-equivalent FWHM bunch length and $(3.79\text{-}3.91)\times10^{-4}$ ppb relative momentum spread, which is smaller than nominal. A proportionally larger voltage is required to capture bunches arriving with a larger momentum spread, as for batches of 72 bunches, for instance.

3 Maximum achievable voltage

In the half-detuning beam loading compensation scheme [2], the average power consumption P for superconducting cavities is given by the RF voltage per cavity V and the beam peak current I_{pk},

$$P = \frac{V I_{\mathsf{pk}}}{8} \,. \tag{1}$$

The maximum achievable voltage in the RF system depends thus on the maximum power of the klystrons and the beam current.

The present LHC RF klystrons have two operational working points, see Table 1. The product of the klystron high voltage (HV) and the cathode current determines the DC power of the klystron; 500 kW is the nominal value the klystrons are rated for. An efficiency of 60 %, the design value [5], was assumed to calculate the RF power. However, the efficiency can degrade with time due to ageing, and there is little margin in the cathode current (both from the klystron and the power converter point of view) to compensate for decreased efficiency by increased current. The maximum klystron forward power measured in saturation measurements gives actually lower readings, with some spread from one line to another.

Klystron HV	**Cathode current**	**DC power**	**RF power**	**Measured saturation**
50 kV	7.8 A	390 kW	230 kW	190-220 kW
58 kV	8.6 A	500 kW	300 kW	250-280 kW

Table 1: Present LHC klystron working points.

As the exact value of the forward power fed into a cavity depends on calibration, reflected power, and many other factors, we focus on the maximum voltage achievable with beam loading rather than the maximum power available from the klystrons. To determine this voltage limit, we have performed beam measurements [8] with all cavities optimised in terms of loaded Q and tuner phase in order to maintain the maximum possible voltage with beam.

In the cavity, the steady-state beam loading is obtained typically with about 40 bunches spaced by 25 ns. Having batches of 48 or 72 consecutive bunches does therefore not make a difference. However, over the first ∼40 bunches or shorter batches, significant power transients occur.

For a klystron high voltage of 50 kV, an average injected bunch intensity of 1.15×10^{11} ppb, a BCMS beam with batches of 144 bunches (3×48 bunches with gaps of 200 ns), and a cavity loaded Q of 40 000, the total voltage of 9 MV (1.125 MV/cavity) was at the very limit of being operable. With all lines saturating, the cavity voltage was just being maintained and several batches of 144 bunches were still kept stably in the machine. By changing the loaded Q of the cavities to 35 000 or 45 000 and re-injecting 144 bunches, the beams got dumped right at injection due to cavity trips.

Note that the power transients at the first injection of a 144-bunch batch are always stronger than for consecutive injections, as the cavity tune is not optimal at this moment. A predictive detuning, as originally foreseen but not implemented, could help to push the limits of the RF system somewhat further. It cannot, however, overcome the limits of saturation seen with 9 MV and several batches in the machine.

Taking into account some operational margin, the total voltage of 8 MV is considered to be the maximum achievable voltage with 50 kV high voltage and a bunch intensity of 1.15×10^{11} ppb.

4 Operation at increased intensities

4.1 Expected beam parameters from SPS

When scaling the operational parameters to what is expected at increased intensities, one should bear in mind that the present measurements were done with the BCMS beam that is smaller than nominal. The LIU baseline parameters for SPS extraction [9] have been determined for an average extracted bunch length of 1.65 ns, which is the minimum bunch length observed with 25 ns beam and 72 bunches per batch, with four batches and nominal intensity. It should be noted that the bunch-to-bunch intensity and bunch length spread is expected to increase with increased intensities, which could be crucial for capture losses in the LHC.

For beam stability, the upgraded maximum RF voltage of 10 MV at 200 MHz is planned to be used at flat top for a beam intensity of 2.3×10^{11} ppb. This was originally the baseline for the Q20 optics (gamma transition of 18.0); however, even if the Q22 optics (gamma transition of 20.0) will be used, the same extraction voltage can be used to recuperate the stability margin lost due to the optics by a larger momentum spread, see Table 2.

Bunch intensity	**Optics**	**Production scheme**	**RF voltage**	**Rel. momentum spread**	**Emittance**
1.15×10^{11} ppb	Q20	BCMS	7 MV	$(3.79\text{-}3.91)\times10^{-4}$	0.40-0.42 eVs
1.15×10^{11} ppb	Q20	standard	7 MV	4.14×10^{-4}	0.48 eVs
2.3×10^{11} ppb	Q20	standard	10 MV	4.95×10^{-4}	0.57 eVs
2.3×10^{11} ppb	Q20	standard	10+2 MV[1]	5.29×10^{-4}	0.57 eVs
2.3×10^{11} ppb	Q22	standard	10 MV	5.50×10^{-4}	0.63 eVs

Table 2: Expected SPS beam parameters at extraction to LHC; calculated from a pure 200 MHz bucket, except for line 4, where an extra 2 MV at 800 MHz were assumed.

Furthermore, after the LIU upgrade of the SPS RF system, one can expect that up to 2 MV RF voltage at 800 MHz will be used for beam stability, which starts to have a non-negligible impact on the momentum spread of the extracted bunches (see fourth line in Table 2). On the other hand, potential-well distortion will somewhat reduce the momentum spread at SPS flat top, and this reduction increases with bunch intensity.

By the end of Run III, a bunch intensity of 1.8×10^{11} ppb is targeted for LHC injection [10]. The SPS extraction parameters at this intermediate intensity are expected to be similar to the high-intensity parameters in Table 2. This is because with 2.3×10^{11} ppb and 10 MV,

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[1] 10 MV at 200 MHz and the maximum available 2 MV at 800 MHz

the beam is at the limit of stability, and using the maximum available voltage even with a reduced intensity helps to make bunches as short as possible, thus minimising halo particles and associated losses, and leaving a more comfortable stability margin for operation.

4.2 LHC injection voltage requirements

Accounting for the larger momentum spread arriving from the SPS in the future, the LHC injection voltage has to be increased from the absolute minimum of 4 MV with the present (3.79-3.91)$\times 10^{-4}$ momentum spread to at least 6.4-6.8 MV in the Q20 option, both for 1.8×10^{11} ppb and 2.3×10^{11} ppb. The Q22 option demands a larger capture voltage of 7.9-8.4 MV.

The power available at 58 kV klystron HV is 30 % larger than with 50 kV HV. With the maximum power, the maximum voltage available is 10.4 MV at 1.15×10^{11} ppb, 6.6 MV at 1.8×10^{11} ppb, and 5.2 MV at 2.3×10^{11} ppb. The present RF system can thus barely cope with the 1.8×10^{11} ppb demanded by the end of Run III, and cannot deliver enough voltage for HL-LHC intensities as is.

It should be taken into account that these estimates are optimistic. They do not take into account the ageing of the klystrons, the increased bunch-by-bunch intensity and bunch length spread with increased intensities, the large injection errors (in phase and/or energy) between the SPS and the LHC paired with possibly stronger injection oscillations at high intensities, or the use of the PPLP ramp in the LHC, for instance, where start-of-ramp losses will be enhanced, too.

5 Recommendations

Studies on several options and improvements concerning the LHC main RF system should be launched in parallel. These studies concern:

1. A batch-by-batch longitudinal damper to correct injection errors and damp bunch oscillations;
2. A feed-forward on the cavity detuning for the injection of the first long batch that causes the strongest power transients;
3. High-efficiency klystrons for replacing the present klystrons;
4. Partial full-detuning at LHC injection or full-detuning at SPS extraction.

6 Conclusions

Beam studies using the present LHC RF system have shown that 4 MV is the absolute minimum capture voltage that can be used with the present beam quality arriving from the SPS. Also in machine studies, the maximum affordable voltage was found to be 8 MV with 50 kV klystron high voltage at the present beam intensities, accounting for some operational margin.

Future beam parameters will require about 6.4-6.8 MV or 7.9-8.4 MV capture voltage in the LHC, with the Q20 and Q22 optics used in the SPS, respectively. The available maximum voltage is estimated to be 6.6 MV at 1.8×10^{11} ppb, and 5.2 MV at 2.3×10^{11} ppb.

An upgrade of the present LHC RF system might be necessary to digest future high intensities. Studies on high-efficiency klystrons, and different low-power RF feedbacks and operational scenarios have to be performed to evaluate how the limitations of the present system can be overcome.

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References

[1] Apollinari, G. and Béjar Alonso, I. and Brüning, O. and Lamont, M. and Rossi, L. *High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report.* CERN Yellow Reports: Monographs. CERN, Geneva, 2015.

[2] D. Boussard. rf power requirements for a high intensity proton collider ; parts 1 (chapters I, II, III) and 2 (chapters IV, V, VI). Technical Report CERN-SL-91-16-RFS, CERN, Geneva, Switzerland, May 1991.

[3] Mastoridis, T. and Baudrenghien, P. and Molendijk, J. Cavity voltage phase modulation to reduce the high-luminosity Large Hadron Collider rf power requirements. *Phys. Rev. Accel. Beams*, 20(10):101003. 13 p, 2017.

[4] Timko, H. and Baudrenghien, P. and Brunner, O. and Butterworth, A. and Shaposhnikova, E. and Turaj, K. and Valuch, D. LHC RF system performance in 2017. In *Proc. Evian 2017 workshop, Evian, France*, 2017.

[5] Brüning, O. and Collier, P. and Lebrun, P. and Myers, S. and Ostojic, R. and Poole, J. and Proudlock, P. LHC Design Report. Technical report, CERN, Geneva, Switzerland, 2004.

[6] Timko, H. and Argyropoulos, T. and Karpov, I. and Shaposhnikova, E. Beam instabilities after injection to the LHC. In *Proc. HB2018 workshop, Daejeon, Korea*, 2017. TUP1WA03.

[7] Timko, H. and Argyropoulos, T. and Baudrenghien, P. and Buffat, X. and Karpov, I. and Palm, M. and Salvachua Ferrando, B. and Shaposhnikova, E. Injection voltage reduction in the LHC. Presentation at the LHC Machine Committee, 2018.

[8] Timko, H. and Baudrenghien, P. and Calaga, R. and Karpov, I. and Peaguet, F. and Turaj, K. LHC MD3165: RF power limitations at flat bottom. CERN internal note to be published, 2018.

[9] Damerau, H. and Funken, A. and Garoby, R. and Gilardoni, S. and Goddard, B. and Hanke, K. and Lombardi, A. and Manglunki, D. and Meddahi, M. and Mikulec, B. and Rumolo, G. and Shaposhnikova, E. and Vretenar, M. and Coupard, J. LHC Injectors Upgrade, Technical Design Report, Vol. I: Protons. Technical Report CERN-ACC-2014-0337, CERN, Geneva, Switzerland, Dec 2014.

[10] Fartoukh, S. and Karastathis, N. and Papadopoulou, S. and Papaphilippou, Y. and Sterbini, G. Preliminary performance estimates for Run III operation. Presentation at the LHC Run III Configuration WG, 2018.