UPGRADE OF THE 200 MHz RF SYSTEM IN THE CERN SPS

E. Shaposhnikova, E. Ciapala, E. Montesinos, CERN, Geneva, Switzerland

Abstract

The 200 MHz RF system used in the SPS for acceleration of all beams including the LHC-type ones has a travelling wave structure and consists of four cavities, two of them with five sections and two with four. For stability of future high intensity LHC beams in the SPS larger (than now) controlled longitudinal emittance blow-up and therefore bucket and voltage amplitude will be necessary, but less voltage will be available due to the effect of beam loading in the existing system with maximum peak RF power per cavity of 1 MW. This issue will become critical for beam acceleration and especially for beam transfer into the 400 MHz RF system of the LHC. The proposed solution is to shorten the two long cavities and using free sections together with two spare to install two extra cavities with corresponding power plants of 1.4 MW each. After this upgrade, which is a main part of more general SPS upgrade for high luminosity LHC and should be completed during 2017, the performance of the SPS RF system with high intensity beams will be significantly improved and at the same time the overall peak impedance of the system will be reduced by 20%.

PRESENT STATUS AND MOTIVATION

At the moment the SPS is able to deliver at top energy (450 GeV/c) the LHC beam (4 batches of 72 bunches spaced at 25 ns) with nominal intensity of 1.2×10^{11} per bunch. This beam has longitudinal emittance of 0.63 eVs. With voltage of 7 MV at 200 MHz bunch length is 1.7 ns (4σ Gaussian shape), fitting well the 400 MHz RF bucket of the LHC [1]. During this (2011) year of LHC operation only the beam with a 50 ns bunch spacing has been requested by LHC, with maximum average bunch intensity of 1.6×10^{11} achieved so far on the flat top in 4 batches of 36 bunches.

The 200 MHz RF system is used for acceleration of these beams at harmonic h=4620 from injection (26 GeV/c) to top energy (450 GeV/c) together the 800 MHz RF system used for beam stabilisation. In the future the SPS should be able to reliably accelerate much higher beam intensity. Various LHC upgrade scenarios are presently under consideration [2], see Table 1. From the RF point of view the most demanding are those based on beam with 25 ns spaced bunches with ultimate (1.8×10^{11} p/bunch) and even higher bunch intensity. As will be shown below the present RF system is not able to satisfy future needs [3]. The upgrade of the RF system is an essential part of more general SPS upgrade in the frame of approved LHC Injector Upgrade project [4].

Table 1: Performance achieved in the SPS up to now for nominal beams and future possible requests, 450 GeV.

Beam Type		LHC nom.	CNGS nom.	LHC ult.	LHC upgrade
spacing	ns	25	5	25	25
N_b	10^{11}	1.2	0.115	1.8	2.3
n_{bunch}		288	4200	288	288
N_{tot}	10^{13}	3.5	4.8	5.2	6.6
I_{rf}	A	1.54	0.73	2.3	3.0
ε_L	eVs	0.6	0.8	< 1	< 1

Beam Loading

The two RF systems in the SPS, 200 MHz and 800 MHz, are both of TW (travelling wave) type. The 200 MHz RF system consists of 2 cavities of 5 sections and 2 cavities of 4 sections. Each section has 11 cells. The required power in one TW cavity with n sections for zero slip factor is [5]

$$P_n = V_n^2/(RL_n^2) + RL_n^2 I_{rf}^2/64 + V_n I_{rf} \sin\phi_s/4,$$

where $R = 27.1\ \mathrm{kOhm/m^2}$, interaction length $L_n = L_0(11n-1)$, $L_0 = 0.374$ m and $I_{rf} = 2FN_b e/T_{bb}$ with $F \simeq 1$ for short bunches. Presently the maximum total voltage available at nominal LHC intensity is 7.5 MV. The power per cavity is limited by power amplifiers, fundamental power couplers and feeder lines to 700 kW in continuous operation (full ring, CNGS type beam) and up to 900 kW in pulsed operation (LHC beam). With an adequate upgrade of the present equipment a higher value of 1.0 MW is possible in pulsed mode for an LHC beam filling less than half of the ring. The power per 200 MHz cavity during the LHC cycle in the SPS is shown in Fig. 1 for cavities of different length. It corresponds to the voltage program with maximum of 4.5 MV during the ramp and 7.5 MV on the flat top. The 800 MHz voltage during the cycle usually follows the 200 MHz voltage program at 1/10 level. After the ongoing upgrade the 800 MHz RF system, its required power will be well below limitations.

Longitudinal Coupled Bunch Instabilities

The longitudinal coupled-bunch instability of the LHC beam in the SPS is characterised by a very low intensity threshold which is approximately proportional to the inverse of beam energy [3]. A single LHC batch with 2×10^{10} p/bunch becomes unstable during acceleration above ~ 200 GeV/c with feedback and feedforward systems in operation. At injection the coupled-bunch instability is observed at $\sim 1.1 \times 10^{11}$/bunch.

To stabilise the beam, controlled emittance blow-up is performed twice during the cycle, in addition to the use of the 800 MHz RF system as a Landau cavity in bunch-shortening mode throughout the cycle. The first blow-up is with mismatched voltage at injection; due to filamentation the initial emittance of 0.35 eVs is increased to 0.42 eVs. The second takes place at around 200 GeV/c, with band-limited noise which blows up the emittance to 0.6 eVs. The SPS Beam Quality Monitor [6] controls bunch lengths preventing extraction to LHC of beam with too long bunches.

For ultimate LHC intensities controlled emittance blow-up to at least 0.75 eVs will be needed to stabilise the beam. It is also possible that for these high intensities larger longitudinal emittances are required at 450 GeV in LHC itself. Then beam transfer to the LHC 400 MHz RF system from the SPS 200 MHz RF system becomes critical and several solutions were considered: (1) to install the 200 MHz RF system in LHC; (2) to increase the voltage at extraction in the SPS 200 MHz RF system.

Apart from controlled emittance blow-up another possibility to improve beam stability is to use optics with lower transition energy ($\gamma_t = 18$ instead of nominal 22.8) [7], since thresholds of both coupled bunch instability and loss of Landau damping are proportional to the slippage factor $\eta = 1/\gamma^2 - 1/\gamma_t^2$. However in this case to obtain for fixed emittance at the SPS extraction the same bunch length, the 200 MHz voltage should also be η times (1.6 at 450 GeV) higher. First tests confirm that with lower γ_t the beam is more stable and the emittance required for stability in the SPS is smaller [7]. However if smaller emittances are not acceptable in LHC (beam stability or IBS) more voltage is needed in the SPS with $\gamma_t = 18$.

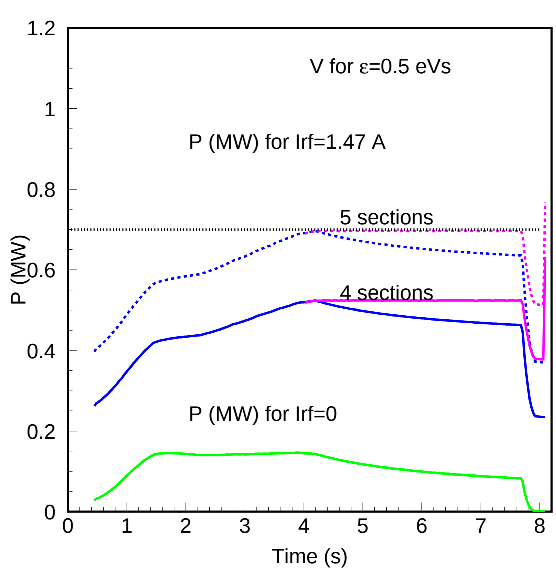

Figure 1: Power per SPS 200 MHz cavity having 4 or 5 sections for nominal and zero (green) beam current during the LHC cycle with two voltage programs (blue - voltage for constant filling factor in momentum for emittance of 0.5 eVs, red - constant 4.5 MV at the end of the cycle increased to 7.0 MV prior extraction to LHC).

RF UPGRADE

As was discussed above, more voltage is required for transfer of beams with larger emittance to LHC. On the other hand, the existing two 5-section cavities can provide much less voltage already at ultimate LHC current for power limit of 1.4 MW/cavity [8] and become practically useless with 1 MW/cavity, Fig. 2.

Two possible solutions to this problem is to rearrange the existing 4 cavities (with 2 spare sections) into 5 or 6 cavities of shorter length with 1 or 2 extra power plants which allow simultaneously to reduce beam loading per cavity, increase available voltage and even reduce total beam coupling impedance.

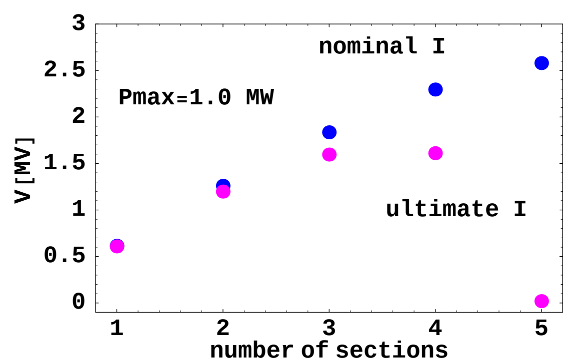

Figure 2: Voltage from one SPS 200 MHz TW cavity having different number of sections for nominal (top circles) and ultimate (bottom circles) beam current.

Total beam coupling impedance of the 200 MHz TW RF system (peak value at fundamental frequency) is [5]

$$Z = \frac{R}{8} \sum L_n^2.$$

The two most promising options for RF configuration are presented in Table 2 together with the actual situation. Even with two extra (spare at the moment) sections (the case of 6 cavities) the total impedance of shorter cavities will be $\sim$ 20% less than now.

The present power limitation applied per cavity for reliable operation is 700 kW cw. The existing configuration can only provide 4 MV at ultimate current even at 1 MW/cavity. With 6 cavities and power of 1 MW the same voltage can be obtained for ultimate current as now for nominal. In Fig. 3 maximum total voltage achievable for nominal and ultimate current with different RF configurations from Table 2 is shown as a function of RF power available per cavity.

The 6 cavity option gives the largest gain, especially for higher available power. The proposal under study at the moment, see Fig 4, is to build two new power plants with

Table 2: Beam coupling fundamental impedance Z and voltage V available at 450 GeV/c (for ultimate and twice nominal current with 1 MW power limit) with possible future configurations of the 200 MHz RF system in the SPS and the actual one (first row).

Total Number n_{cav}	n_{cav} with n_{sect}			Z MΩ	V [MV] for 1 MW		
	3	4	5		1.54 A	2.3 A	3.0 A
4	0	2	2	4.5	9.9	6.5	0
5	2	3	0	3.6	10.6	8.8	3.6
6	4	2	0	3.7	12.7	10.3	5.9

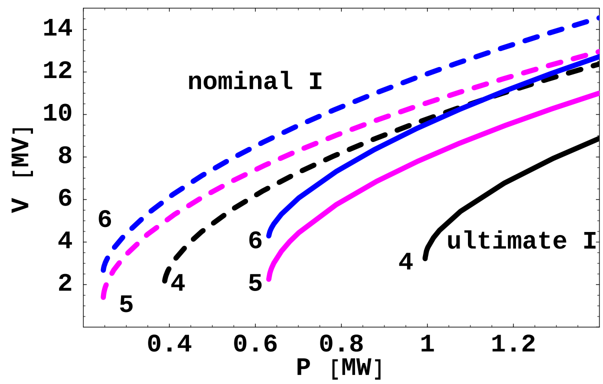

Figure 3: Total voltage possible for nominal and ultimate LHC intensity for different RF configurations from Table 2 with 4 (present situation), 5 or 6 cavities as a function of power limit per cavity.

1.4 MW pulsed at the cavities input for two 4-section cavities, and upgrade present four power plants to reach 1.0 MW pulsed for four other 3-section cavities. The total voltage possible at 450 GeV for present and future situations is shown in Fig. 5 as a function of beam current.

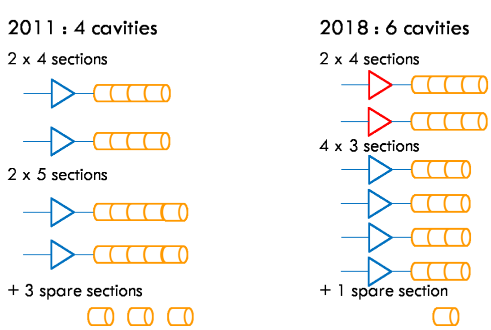

Figure 4: Proposal for cavity and power upgrade

For the 6 cavity option the gain in available voltage (for a given current) is even more significant for fast cycles (CNGS type beam) with short acceleration time. Presently both voltage and power are at the limit since 7.5 MV is used after transition crossing. With 6 cavities almost 30% more voltage will be available for a given current or twice higher

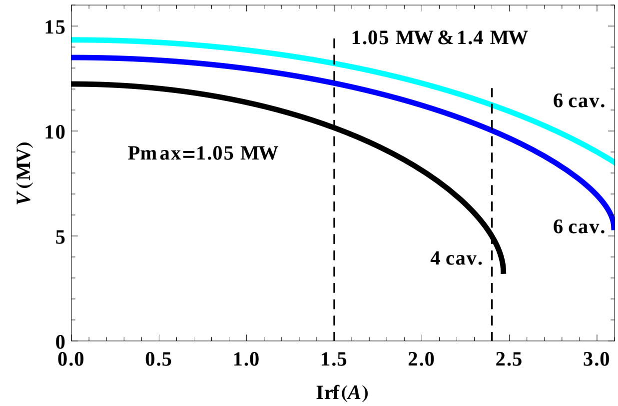

Figure 5: Total voltage possible on the flat top with 4 (present situation) and 6 cavities as a function of beam current for two options of power upgrade for 6 cavities (top curve - 1.05 MW per each 3-section cavity and 1.4 MW for each 4-section cavity; middle - 1.05 MW/cavity). Dashed lines are at nominal and ultimate beam currents.

current can be accelerated with the same voltage (implies longitudinal emittance control). Similar improvement can be expected for the fast LHC cycle.

SUMMARY

The increased number of shorter (than present) 200 MHz cavities with 2 extra power plants should significantly improve the RF performance for ultimate and upgrade LHC intensities as well as for optics with low transition energy. This modification will also reduce the peak impedance and hopefully remove the need in installation of the capture (200 MHz) RF system in LHC. The implementation of the project has started this year and should be completed in 2017.

ACKNOWLEDGMENTS

We are grateful to the colleagues from the SPSU Study Group and LIU-SPS coordination team for their support. We would like also to thank our colleagues T. Bohl and T. Linnecar for useful discussions on RF upgrade.

REFERENCES

[1] T. Bohl *et al.*, CERN BE-Note-2009-016 MD.

[2] Talks at CERN mini-Chamonix workshop, July 2011.

[3] E. Shaposhnikova, Proc. workshop Chamonix 2010, CERN-ATS-2010-026.

[4] R. Garoby *et al.*, these Proc., WEPS017.

[5] G. Dome, Proc. Proton Linear Acc. Conf., Ontario, 1976, p.138.

[6] G. Papotti, T. Bohl, E. Shaposhnikova, these Proc., TUPZ021.

[7] H. Bartosik *et al.*, these Proc., MOPS010.

[8] T. Bohl, Proc. workshop Chamonix X, 2000.