A 200 MHz SC-RF SYSTEM FOR THE HL-LHC *

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Abstract

A quarter wave $\beta = 1$ superconducting cavity at 200 MHz is proposed for the HL-LHC as a complement to the present 400 MHz RF system. The advantage of such a system would be to accelerate higher intensity and longer bunches with improved capture efficiency. Advantages related to minimizing electron cloud effects, intra-beam scattering, heating and the possibility of luminosity leveling with bunch length are described. Some considerations related to longitudinal beam stability, cavity optimization, beam loading and technological challenges are addressed.

INTRODUCTION

A sub-harmonic RF system at 200 MHz is proposed to replace the existing 400 MHz accelerating RF system in the LHC. The main goal for a lower frequency RF system is to improve the capture efficiency between the SPS and the LHC, accelerate and store very high intensity and long bunches as an alternative to the present HL-LHC baseline [1]. From stability considerations, this scenario will imply an operating bunch length of 1.7-2.0 ns (4σ). Part of the present RF system at 400 MHz is therefore retained to provide the required voltage at the second harmonic to increase the operating range between 1.35-2.0 ns [2, 3]. It also provides the possibility of recapturing the stored beam during physics to reach smaller bunch lengths (1 ns) or perform additional bunch profile manipulations.

This system provides an alternative scenario for luminosity optimization to reach the same integrated luminosity goals of HL-LHC while mitigating the electron cloud effect [4]. The ability to capture more intense (up to 2.5×10^{11}) and longer bunches with reduced RF heating is vital. RF heating in the LHC is already observed as an issue to be mitigated [5]. The ability of the injectors to provide the high intensity is outside the scope of this paper. However, intensities up to 2.4×10^{11}p/bunch from the SPS were shown to be feasible in simulations with the foreseen RF upgrade and ramp cycle manipulations [3, 6].

TECHNOLOGY CHOICE

A normal conducting 200 MHz system was already planned as a capture system if the extracted emittance from the SPS becomes large [7]. Then the bunches are adiabatically transferred to the 400 MHz system (ACS-400) prior to energy ramp. Due to physical size constraints, a superconducting system at 200 MHz with conventional elliptical cavities was discarded at that time.

However, a new concept using $\lambda/4$ resonators at frequencies of 200 MHz or below became attractive. A similar system was conceived at 56 MHz for the RHIC accelerator [9]. Figure 1 shows two such geometries at 200 MHz as a part of the cavity optimization from the initial $\lambda/4$ resonator presented in Ref. [2] is referred to as version 1.

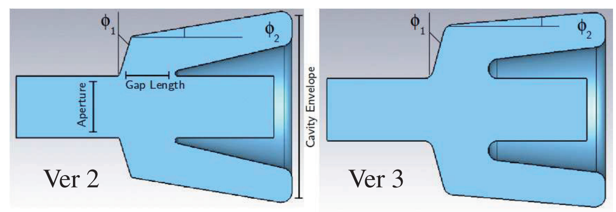

Figure 1: Design evolution of a 200 MHz $\lambda/4$ resonator from the original proposal in Ref. [2].

Table 1 shows relevant RF parameters of the 200 MHz system for two models compared to the existing RF system. It is important to note that the $\lambda/4$-resonator is approximately 20% smaller in transverse size as compared to the existing ACS-400 MHz system. The required maximum voltage per cavity of 2 MV is easily reached with the corresponding peak surface fields for all models.

Table 1: Relevant Cavity Parameters for the 200 MHz Compared to ACS-400

	Ver 2	Ver 3	ACS-400
Frequency [MHz]	200.3	200.3	400.7
Voltage [MV]	2.0	2.0	2.0
Cavity Type	co-axial	co-axial	ellip
Gap Length [mm]	133.5	150	377.3
Aperture [mm]	168	180	300
Cav. Envelope [mm]	284	284	344
E_p, B_p [MV/m, mT]	29, 68	38, 65	12.5, 30
R/Q (circuit) [Ω]	51	47	45
$G = R_s Q_0$ [Ω]	51	68.4	-

The optimization procedure is carried out in two steps. Using the initial design (Ver 1) as in the reference [2], the cavity wall angles (θ_1, θ_2) in Figure 1 are scanned keeping the aperture and gap length constant. Figure 2 shows a contour plot of ratio of the peak surface fields normalized to the cavity voltage. Two possible working points are shown in Figure 1. Ver 3 is favorable due to manufacturing considerations [8]. The 2^{nd} optimization step is underway to determine the appropriate gap length and aperture. The relative angles between the two walls of the resonator might need adjustment from multipacting considerations.

* The research is supported by the High Luminosity LHC project

ISBN 978-3-95450-147-2

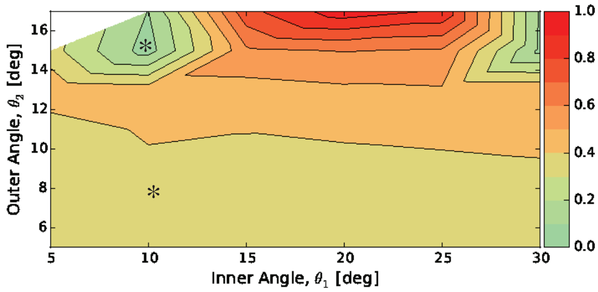

Figure 2: Contours of the ratio of peak surface fields E_p/B_p normalized to the accelerating voltage as a function of the wall angles shown in Figure 1. The gap length and the aperture were kept constant.

Cavity Impedance

Apart from the compact size at low frequency, a significant advantage of $\lambda/4$ resonator is the large spacing between the accelerating mode and the higher order modes (HOM). For a pure $\lambda/4$ quarter resonator, it can be shown that longitudinal modes exist at frequencies that satisfy the transcendental equation $Z_0 \tan(\beta l) = 1/(\omega C_{gap})$. Therefore, the first HOM exists at approximately 3 times the fundamental which makes the damping scheme simpler. Figure 3 shows an impedance spectrum for longitudinal and transverse modes for the initial design (Ver 1) as a reference illustrating the few number of HOMs up to a range of 8 times the fundamental frequency. It should be noted that the impedance values are not completely resolved and the amplitude is only qualitative. Strong HOM damping maybe required to be within the impedance tolerances of HL-LHC.

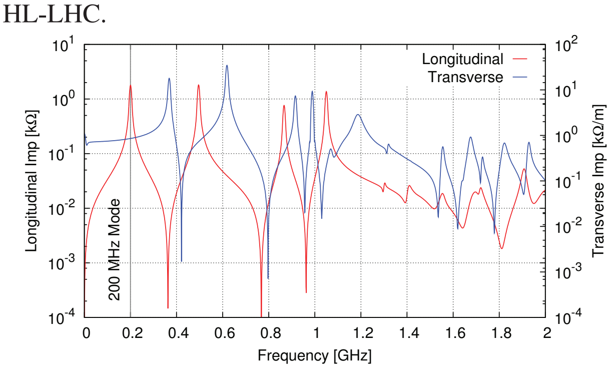

Figure 3: Longitudinal and transverse impedance for the $\lambda/4$ design (Ver 1) at 200 MHz as a function of frequency.

RF Voltage & Power

Although, only a minimum of 3 MV is required to inject, ramp and store the LHC beams [3], 6 MV is assumed. Figure 4 shows the bunch length as a function of the longitudinal emittance at injection and at flattop in a single (200 MHz) and a 2$^{\text{nd}}$ (200 + 400 MHz) harmonic RF system. A minimum stable emittance in the 200 MHz at injection energy is estimated to be 1 eVs while at flattop is 3 eVs in the 200 MHz system alone [3]. It would be a natural choice to use the existing ACS-400 to achieve smaller bunch lengths ($\leq$ 1.5ns). The voltage requirement is mod-

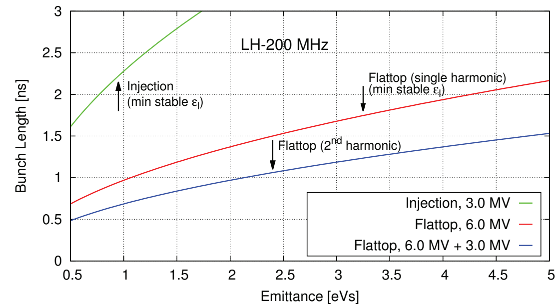

Figure 4: Bunch length vs emittance for inj. and flattop voltages in the 200 MHz with and w/o the 2^{nd} harmonic.

est in both systems as opposed to using only a 200 MHz RF system. In addition, the ACS-400 MHz system as a second harmonic could help to provide stability for smaller longitudinal emittances. Figure 5 shows that with an optimized Q_L of approximately 2×10^4, the forward power in the 200 MHz system in the $1/2$-detuning scheme is approximately 420 kW. Existing expertise from the SPS and the LHC can be used to develop a power coupler and the RF chain capable of handling power levels of 500 kW. The Q_L is also compatible at injection energy with a large enough bandwidth to act against injection transients. Therefore fixed coupling could be considered, thus greatly easing the design of the high power coupler. Power sources at this frequency and power levels already exist (diacrodes).

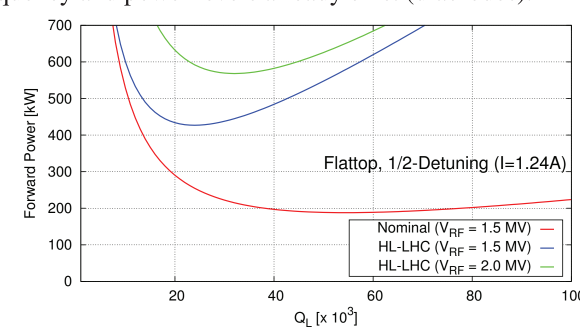

Figure 5: Forward RF power as a function of Q_L at flat Top for a 200 MHz RF system assuming I_b = 1.24 A.

If the maximum voltage is limited to 6 MV in the 200 MHz system, four cavities per beam will be sufficient. With this configuration, a maximum of only 3 MV in the 400 MHz is sufficient to provide the RF voltage at the 2^{nd} harmonic. This can be easily provided from an existing single 4-cavity module or possibly even with only two cavities. With the addition of the 2^{nd} harmonic, the bunch lengths can be brought down to approximately 1.35 ns in the BS-mode and well beyond 1.8 ns in the BL-mode [3].

ALTERNATIVE LUMINOSITY SCENARIO

The option of using a lower frequency cavity at 200 MHz opens a new regime of operation with long bunches with increased current by 10% or more compared to HL-LHC baseline. This option in conjunction with the existing 400 MHz RF system provides several advantages including a bigger margin for luminosity leveling.

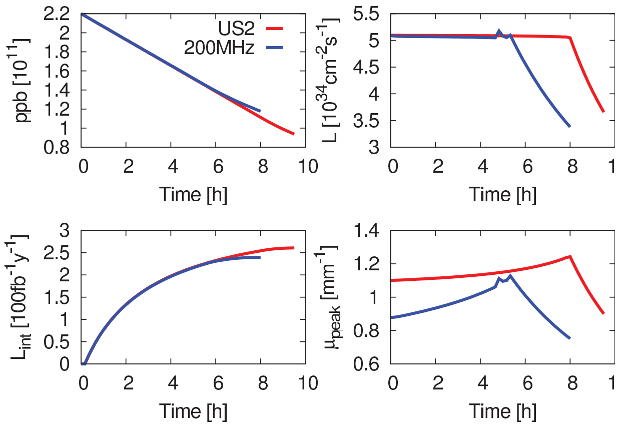

Figure 6: Comparison of the HL-LHC baseline (red) to the alternative of 200 MHz (blue). A bunch length of 15 cm at collision and 20 cm at injection and β^*-leveling is assumed.

Benefits of Longer Bunches

Electron cloud is a critical issue at injection for transverse emittance dilution (due to the lower beam rigidity) and during the ramp for the total heat deposition in the beam screens (due to the extra sources of heat load). Simulations show (see Ref. [4]) that for bunch lengths above 2.5 ns, the effect of electron cloud in dipoles can be completely suppressed with expected SEY of 1.4-1.5. It is however interesting to note that for SEYs lower than 1.3, the heat load increases for longer bunches.

At top energy the optimal bunch length needs to be defined considering luminosity performance and heat load together. Assuming a conservative approach, a bunch length of 2 ns at top energy is assumed in the simulations. Figure 6 compares the HL-LHC baseline fill evolution to the 200 MHz alternative. Performance in integrated luminosity is reduced only by about 7% compared to that of the HL-LHC baseline. No performance degradation is expected if the complete 400 MHz system is retained to re-capture the beam during physics. In the $1/2$-detuning scheme the beam current needs to be low enough to be accommodated with the present RF power limits on the 400 MHz system.

Main Limitations

The main limitation from a lower RF frequency is the reduction of the TMCI threshold due to the lower synchrotron tune and longer bunch. Using a bunch length of 12.6 cm and $Q_s = 9 \times 10^{-4}$ for the 200 MHz scenario the relative reduction of the TMCI threshold is 1.36. The degradation by about a factor 1.5 is confirmed and the threshold is decreased to 2.6×10^{11} ppb which is marginally above the foreseen operational bunch charge. Multi-bunch effects might slightly decrease this threshold further. However, it was shown that the use of transverse damper and chromaticity can increase intensity thresholds in various machines [10].Another concern of the 200 MHz system is its compatibility with 400 MHz crab cavities. An illustration of the beams encounter at the IP is depicted in Figure 7 for the baseline and the 200 MHz alternative. The core of the

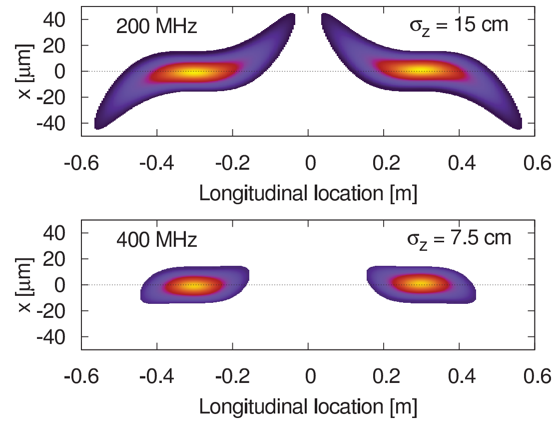

Figure 7: Crab cavity RF curvature and its effect on the collision for present 400 MHz (bottom) and the alternative at 200 MHz (top). The beams contours correspond to 2 σ envelope for a β^*= 15 cm.

beam (1 σ corresponding to the red area) is unaffected by the crab cavity RF curvature. Weak strong DA simulations for the configuration of 200 MHz as a main RF and a crab cavity of 400 MHz show no significant change [4].

CONCLUSIONS

A new scheme to use a lower frequency RF cavities as the main RF system is proposed for the HL-LHC. The new regime of operation of HL-LHC with longer and more intense bunches was described along with the advantages related to luminosity and beam stability in conjunction with the existing 400 MHz cavities. A first overview of the cavity design optimization, RF power needs and the impedance were outlined. Beam studies and technological feasibility are required to fully validate this scenario.

ACKNOWLEDGMENTS

The authors would also like to extend a special thanks to E. Jensen, E. Montesinos, J. E. Mueller, E. Shaposhnikova.

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ISBN 978-3-95450-147-2