POSSIBLE BEAM PARAMETERS IN DOUBLE RF OPERATION OF THE CERN LHC

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Abstract

The LHC operates using a 400 MHz SC RF system. A 200 MHz NC RF system was foreseen in the LHC Design Report to improve beam capture and the bare resonators were manufactured, but never installed. Later the second harmonic RF system was proposed to cure longitudinal beam instabilities in the absence of a dedicated wide-band feedback system in the LHC. For nominal intensities the longitudinal beam stability is ensured by controlled emittance blow-up during the acceleration ramp. Recently slow growing instabilities were observed at the end of long fills at 6.5 TeV as bunches shrink due to synchrotron radiation damping. For High Luminosity (HL) LHC twice higher intensities should be kept stable with new equipment installed in the ring. Additional motivations for a second RF system in the LHC have also been considered. Operation with an extra RF system is limited by the required RF configuration (phase between the two RF systems) and longitudinal beam stability. In this work requirements for the double RF systems are analyzed together with a possible range of longitudinal beam parameters.

INTRODUCTION

The main RF system in each LHC ring is comprised of eight 400 MHz superconducting (SC) cavities in two cryostats able to provide up to 16 MV per beam. A 200 MHz normal-conducting system, with 3 MV per beam, originally foreseen to reduce beam losses at capture, was finally postponed due to a small longitudinal emittance obtained in its injector, the SPS, following an impedance reduction programme [1]. In absence of a wide-band feedback system the LHC relies on Landau damping provided by the natural synchrotron frequency spread inside the bunch. The second harmonic RF system was proposed to increase the margin for longitudinal beam stability by increasing this spread [2]. Installation of an additional RF system in the LHC has been also considered for many other purposes which could be separated into the two main groups: to have very short or flat bunches. Short bunches (e.g. with bunch length twice less than nominal 1 ns defined as 4σ from a Gaussian fit) were studied initially for the LHC upgrade, but were abandoned finally due to various limitations.

Flat bunches were proposed to alleviate problems related to the beam induced heating, high pile-up and e-cloud effect. Particle simulations and measurements in the LHC have demonstrated that bunches with reduced peak line density can be produced by applying a monochromatic or band-limited excitation of the RF phase with frequencies inside synchrotron frequency band [3]. A flat bunch in a single RF system will evolve with time to a Gaussian shape and in physics run this treatment should be repeated.

At the moment there are two new SC RF systems under consideration [4] in the frame of the HL-LHC project [5], at 800 MHz and 200 MHz. Their parameters and feasible operational modes are discussed below from various points of view. One of the main criteria for the choice of RF parameters is longitudinal beam stability. Single bunch stability in the LHC is defined by the threshold of loss of Landau damping and it was studied in many dedicated experiments [6]. Indeed, as expected and now observed in the LHC, the injected bunches with nominal intensity become unstable and controlled emittance blow-up should be applied during ramp to increase their emittance ε by approximately a factor of 6 [7]. During operation at 6.5 TeV in 2015 [8] practically all 2000 LHC bunches with nominal intensity but larger than nominal initial length (τ = 1.35 ns) became unstable after crossing the threshold for loss of Landau damping (LD) found from measurements with single bunches during the ramp [9], as shown in Fig. 1. This has happened during very long (24 h) fills due to bunch length reduction caused by synchrotron radiation damping.

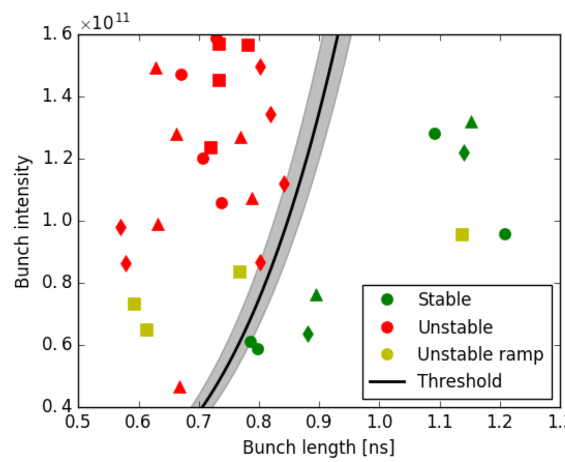

Figure 1: Threshold of loss of Landau damping (black curve) obtained from fitting single bunch instability measurements during the LHC cycle (various symbols) using scaling (1).

During the LHC cycle the intensity threshold N_{th} for loss of LD changes with beam energy E and bunch parameters as [7]

$$N_{th} \propto \varepsilon^2 \tau h^2 / E, \quad (1)$$

where h is RF harmonic number and constant effective impedance ImZ/n was assumed. The present estimation of ImZ/n, confirmed by beam measurements and particle simulations is 0.09 Ohm. So far the nominal LHC beam with 1.15×10^{11} p/b is stable at 6.5 TeV for bunch lengths above 0.9 ns (in the 2015 operational voltage of 10 MV). However twice higher intensity will be needed for the HL-LHC

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with 20% higher impedance budget [10] and preservation of natural Landau damping becomes even more important in absence of a wide-band feedback system.

HIGH HARMONIC RF SYSTEM

A high harmonic RF system was proposed to increase the longitudinal beam stability and provide flexibility in beam parameters (bunch length or emittance) [2]. This method has proven to work well in other rings, including the SPS, where the instability threshold is raised by a factor of 5 using the 4th harmonic RF system with voltage at 10% of the main RF.

The total voltage seen by particle in the double harmonic RF system can be written in the form:

$$V = V_1 \sin\phi + V_2 \sin 2(\phi + \Phi + \delta\Phi), \quad (2)$$

where V_1 and V_2 are the voltage amplitudes of the main and high frequency RF systems, and Φ is the phase shift measured at low frequency. There are two operational modes leading to a significant change in the synchrotron frequency at the bunch center f_{s0}. For non-accelerating bucket (and $\delta\Phi = 0$) above transition the phase shift $\Phi = 0$, corresponding to the bunch-lengthening (BL) mode, decreases f_{s0} and increases the bunch length (for a given emittance). The phase shift $\Phi = \pi/2$ gives bunch-shortening (BS) mode of operation. Maximum changes in f_{s0} are achieved for $V_1/V_2 = 2$.

To deal with high beam-loading in the existing 400 MHz RF system, the full-detuning scheme should be used for intensities higher than nominal [11]. This means that bunches will be shifted from their regular positions and have an additional bunch-by-bunch phase shift in the double RF system. This shift has almost negligible effect in the BSM, but the BLM is much more sensitive to it and the shift deforms bunch profiles significantly. The effect of the phase error $\delta\Phi$ on synchrotron frequency distribution is shown in Fig. 2 for BL and BS modes of operation. As one can see in BS mode the center of the bunch is not affected. The power requirements to keep present half-detuning scheme, which would guarantee the absence of phase errors, make the use of BL mode unfeasible. In simulations bunches can be made flatter even in the BSM by applying phase modulation or band limited noise. Due to increased synchrotron frequency spread BS mode makes also this method of emittance blow-up more robust.

The 800 MHz voltage at a quarter of the main voltage already gives good results for beam stability [6], see Fig. 3. Two different 800 MHz cavity designs, one based on the scaled 400 MHz LHC cavity [12] and another, so called HOM-free cavity [13], were already developed.

LOW HARMONIC RF SYSTEM

Eight (four per beam) bare 200 MHz RF cavities were produced and stored under dry Nitrogen with design based on SPS SWC from the 80's and not suitable for beam acceleration. Preliminary design of a new compact SC quarter-

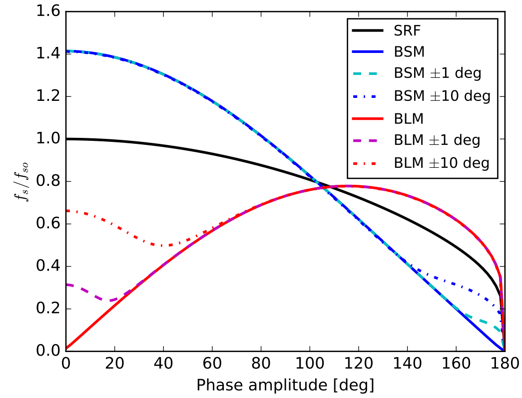

Figure 2: Synchrotron frequency distribution in single (SRF) and double RF system in BL and BS modes for $V_2/V_1 = 2$ and with and without phase error $\delta\Phi$.

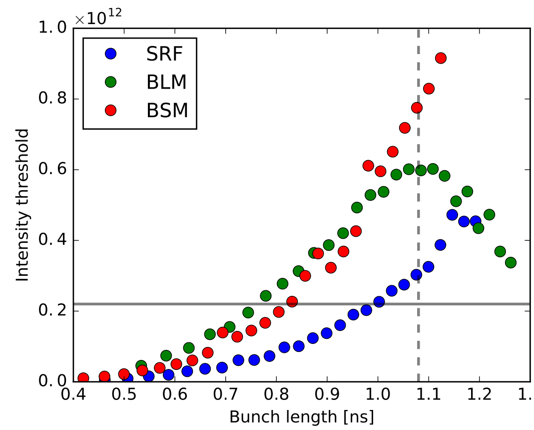

Figure 3: Intensity threshold versus bunch length at 7 TeV from particle simulations for the 400 MHz system with $V_1 = 16$ MV and $V_2 = 0$ (blue), $V_2 = 4$ MV in BS (red) and BL (green) modes.

wavelength cavity now also exists [14]. The 200 MHz RF system, originally proposed as a capture system [1], recently got more attention due to some additional advantages [15]. Longer and flatter bunches could be interesting for improvement of beam-induced heating, e-cloud limitations and pile-up in the experiments. Luminosity leveling, when used with existing 400 MHz RF system (with full voltage), is also considered. This system could also be beneficial on the flat bottom for ions with large longitudinal emittance (reduced IBS effect and capture of bunches after momentum slip-stacking in the SPS). The 200 MHz cavities can be used as a main RF system, see Fig. 4. Voltage of 1 MV per beam would be already sufficient for acceleration of 1 eVs bunches, (0.5 eVs are injected now from the SPS) and it can also be used in BL mode [14].

However as seen from Eq. (1), the longitudinal beam stability in a single 200 MHz RF system is reduced in comparison with 400 MHz RF system and larger emittances are required to keep bunches stable. Operation in a double RF system mode becomes obligatory, but still for the HL-LHC

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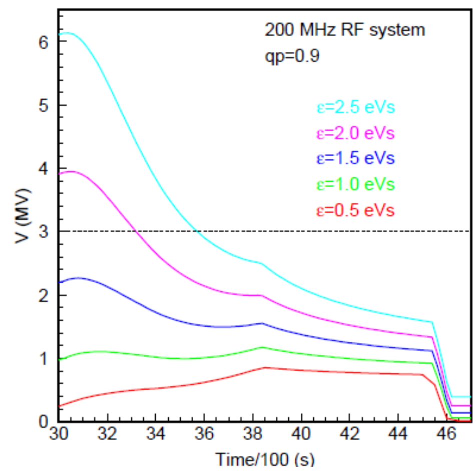

Figure 4: The 200 MHz voltage required during ramp for acceleration with a filling factor in momentum of 0.9 for different longitudinal emittances.

intensity of 2.4×10^{11} only the bunches with length larger than 1.3 ns will be stable, see Fig. 5.

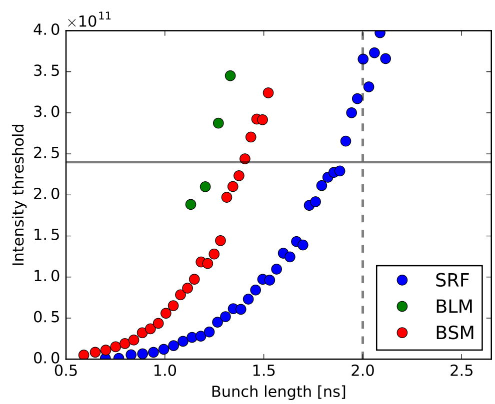

Figure 5: Intensity threshold versus bunch length at 7 TeV from particle simulations for the 200 MHz system with V_1 = 6 MV and V_2 = 0 (blue), V_2 = 3 MV in BS (red) and BL (green) modes.

For the nominal bunch length of 1 ns comparison of instability thresholds in different RF systems and operation modes is shown in Table 1.

SUMMARY

In the present 400 MHz RF system bunches with HL-LHC intensity will be at the limit of stability for a nominal bunch length of 1 ns. Due to bunch length reduction caused by synchrotron radiation damping a continuous emittance blow-up during fill will be needed. The additional 800 MHz RF system with 4 MV RF voltage could significantly increase beam stability providing necessary margin in operation and make controlled emittance blow up more robust. The 200 MHz is an interesting option to have longer bunches at the LHC injection and flat top, however due to reduced beam stability, the 400 MHz RF system will be needed for a double RF operation. With present power limitation in the LHC, BL mode could be feasible only for the 200 MHz RF or with reduced voltage for the 400 MHz RF system. However flatter bunches can also be obtained in a single RF and in double RF system operation for BS mode.

Table 1: Thresholds of loss of Landau damping on the LHC flat top for the nominal 1.0 ns long bunches in a single RF and double RF operation with extra 800 MHz or 200 MHz RF systems in the BS- and BL-modes for the HL-LHC machine parameters [5] and impedance model [10].

RF systems and their operation mode	V_1 [MV]	V_2 [MV]	emit [eVs]	N_{th} $/10^{11}$
400 MHz single RF	16.0	0	2.2	2.2
+ 800 MHz in BSM	16.0	8.0	2.75	8.1
+ 800 MHz in BLM	16.0	8.0	1.45	> 10
200 MHz single RF	6.0	0	1.0	0.1
+ 400 MHz in BSM	6.0	3.0	1.4	0.45
+ 400 MHz in BLM	6.0	3.0	0.35	1.0

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