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An RF System for Landau Damping in the LHC

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Summary

A Landau system in the LHC could significantly increase the longitudinal stability of the LHC beams in the absence of wide-band longitudinal feedback and provide more freedom to define the bunch parameters even during the initial stages of LHC operation. This technique for stabilizing beams, used already in many accelerators, has proven to be very useful in the SPS, raising the instability thresholds by a factor five. One of the luminosity upgrade paths for LHC requires an RF system at 1.2 GHz with ~ 60 MV per beam for bunch shortening. A much smaller RF system at this frequency with ~3 MV per beam would be sufficient to provide Landau damping. This Note analyses the possible benefits and recommends that an R & D programme, leading to one prototype cryostat per ring to be installed in the LHC machine, be launched as soon as possible.

1. Introduction

The main capture, accelerating and storage RF system in the LHC is comprised, for each beam, of eight 400 MHz superconducting (SC) cavities in two cryostats providing up to 16 MV / beam. A 200 MHz capture RF system, providing 3 MV per beam, was originally foreseen to reduce losses at injection. Since the nominal intensity beams now produced in the SPS injector, following a significant upgrade programme, have low emittance, this 200 MHz RF capture system can be "staged" until much higher intensities than nominal are required.

One of the scenarios for a luminosity upgrade in LHC is to provide shorter bunches to permit a lower $\beta*$ in the Intersecting Regions [1]. In order to do this it has been proposed to install a higher frequency superconducting RF system, at 1.2 GHz, with sufficient voltage to reduce the bunch length in coast by a factor 2 (1.06 ns to 0.5 ns at 4σ) [1]. This 1.2 GHz system would have to provide a large RF voltage, ~ 60 MV per beam, and also be able to handle large beam power due to the beam loading [1][2][3]. Recent studies have suggested that an 800 MHz system capable of ~ 70 MV / beam could also be considered and would possibly have some advantages, but the main issues concerning the high accelerating voltage and RF power remain [4]. Another upgrade scenario under review requires very intense flat bunches for which an 800 MHz RF system might also be applicable [5]. A considerable R&D programme is necessary to choose the optimum cavity structure and in particular to find ways around the problem of transferring high RF power into the relatively small diameter cavities, i.e. the RF coupler design, and also extracting large powers at high frequencies, i.e. the HOM design, in what would have to be a superconducting RF system. A further significant area for R&D is to define the power source itself. In a recent White paper [6], presented to Council, resources are described to carry out the initial R&D programme and produce initial prototype cavities.

A higher frequency RF system can also be used as a Landau damping system. For this purpose in the LHC a much lower RF voltage than for bunch shortening is required. The increased Landau damping procured gives more freedom in the choice of beam parameters for a given stability margin and, if required, would provide a better possibility for controlling either single or multi-bunch instabilities than further emittance increase. Note that in the SPS, the LHC injector, such a system, at 800 MHz raises the instability thresholds from 6.0×10^{12} (2.0×10^{10} protons / bunch) to 3.0×10^{13} (1.1×10^{11} protons / bunch). As will be shown below, for Landau damping in the LHC a 1.2 GHz system has certain advantages over other possible frequencies.

Since the voltage requirement is much lower than for the full-blown bunch shortening system it is possible that, at the end of a development phase, sufficient cavities could be made available for a Landau damping system in each ring.

2. The RF and nominal operation

The total RF voltage per beam at 400 MHz will be 8 MV at injection rising to 16 MV in coast. Tuned cavities are necessary to provide the frequency swing during acceleration and also to allow sufficient de-tuning for beam-loading compensation. In addition variable couplers are necessary to optimize the system performance at injection and in coast. This minimizes the power requirement but even so at nominal intensity a power source (klystron) of ~ 300 kW is required for each cavity. Strong feedback systems are required to minimize the cavity impedance both for stability and transient beam loading control. In addition the higher order modes in each cavity must be well damped.

3. Stability considerations

At constant energy the instability threshold condition for single bunch instabilities in the presence of a broad-band impedance Z can be shown to be approximately

$$|\mathrm{Im}Z|/n < A_{BB}\, (\Delta E/E)^2\, \Delta\omega_s/\omega_s\, \tau\, 1/I_b$$

where $\Delta E/E$ is the relative (2σ) energy spread, $\Delta\omega_s/\omega_s$ the relative synchrotron frequency spread, τ the 4σ bunch length and I_b the bunch current.

For coupled bunch instabilities in the presence of a resistance R_{sh} the condition is

$$R_{sh} < A_{CB}\,(\Delta E/E)^2\,\Delta\omega_s/\omega_s\;1/\tau\;1/I_0$$

where I0 is the average beam current, ABB and ACB are constants dependent on machine parameters and energy. The threshold for coupled bunch instabilities also depends on the resonant frequency fres of the source impedance, the worst case, considered here, being when fres ~ 1/τ.

Increasing both energy and synchrotron frequency spreads is beneficial in both cases. There is a different dependence on bunch length for the two types of instability but in the operational modes that we will be considering the threshold doesn't change too much with τ if the emittance ε is held constant. Some caution is required as the theory does not allow for the simultaneous presence of both narrow and broad-band impedance so there can be some uncertainty in the threshold estimations.

Careful estimates have been made of the transverse and longitudinal impedance of the LHC ring using analytical calculations, numerical simulations of different structures and bench measurements. In the transverse plane stability is ensured up to nominal intensity by the presence of a transverse damping system with bandwidth 20 MHz. In addition octupoles can be used to provide extra stability if required. In the longitudinal plane the low frequency inductive impedance seen by the beam is estimated to be ~ 0.1 Ω [7]. Analysis [8] then shows that single bunch instabilities should be well controlled up to nominal intensity provided the longitudinal emittance is increased in a controlled way during the ramp from 1 eVs at injection to 2.5 eVs at 7 TeV. This emittance is also necessary to give IBS growth rates of 60 h for nominal beam. Longitudinal coupled bunch instabilities should also be well controlled up to nominal beam intensities provided that parasitic narrow band resonators in the ring have an impedance below ~ 60 kΩ. As for the single bunch instabilities the controlled emittance increase is equally necessary. The introduction of the new collimator system has reduced the threshold margins in the transverse plane.

There is always the risk that unknown impedances exist in the ring or that the estimations of known structures have some error. As a result it is not excluded that at some intensity instabilities will arise. The bandwidth of the 400 MHz RF system allows instabilities which might develop at low revolution frequency harmonics, to ~ 500 kHz, to be damped - a 20 MHz bandwidth being required to damp all modes. In the event that instabilities arise outside this 500 kHz bandwidth or if single bunch instabilities occur in coast, even extremely slowly growing, the only remedy is to either allow the bunch to increase in emittance or to lower the intensity, both implying a loss of luminosity. There is, at present, no equivalent in the longitudinal plane to the octupoles in the transverse plane.

4. Increasing the instability threshold

To stabilize all possible longitudinal coupled bunch instabilities a separate, wideband (±20 MHz) RF system, for example at 200 MHz, could be built. Previous analysis [9] has shown that it is difficult to make a system that can compete with the damping introduced by the natural spread in synchrotron frequencies in the bunch, even with the short bunches in a single RF system we will have in coast. In addition such a system works for dipole modes and possibly quadrupole modes but not easily for higher bunch modes and cannot help with single bunch instabilities. Therefore if the spread is insufficient the only efficient way of combating all these problems is to increase the spread in the bunch, either by having longer bunches, which is not good for luminosity nor for beam lifetime, or by increasing the non-linearity in the RF waveform by introducing a higher harmonic RF system.

Fig. 1 shows the effect of adding an RF system at 1.2 GHz or 800 MHz on the synchrotron frequency spread inside the bunch at 7 TeV. For this example we have taken an operational storage voltage of 15 MV at 400 MHz. Note that we use the bunch shortening mode which a) has been shown to provide less critical operating conditions [10], b) avoids regions in the bunch where the derivative of the synchrotron frequency, f_s, over synchrotron oscillation amplitude goes to zero and leads to local loss of Landau damping [11], and c) is the mode that would be used later for bunch shortening. The linear f_s is increased by $(1+h_2V_{rf2}/(h_1V_{rf1}))^{1/2}$, where h is the harmonic number and V_{rf} the RF voltage, the subscripts 1,2 referring to the main and higher harmonic RF systems respectively. To avoid multi-potential well formation $V_{rf2} \leq h_1/h_2\, V_{rf1}$. Table 1 summarises some bunch parameter data.

Applying the formula above, which is nonetheless valid only for small perturbations of the particle motion with respect to a single RF system, the gain in stability can be of the order of 3 to 4 times at 7 TeV and at constant bunch length. To gain a factor 2 increase in stability by emittance increase with only the 15 MV 400 MHz system the bunch length would have to increase to ~ 1.3 ns, the emittance increasing from 2.5 eVs to ~ 3.5 eVs. When we have short bunches to start with, voltage at 1.2 GHz is more efficient than at 800 MHz. In this case 3 MV at 1.2 GHz is worth about 7.5 MV at 800 MHz. However 800 MHz has the advantage of not having a “bad” region for any bunch length.

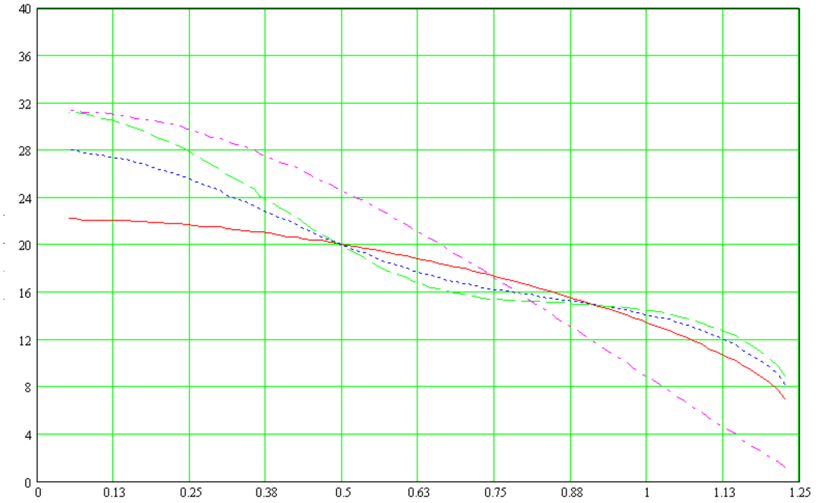

Fig. 1. f_s [Hz] vs amplitude of synchrotron oscillations [ns].

Red: 400 MHz @ 15 MV
Green: 400 MHz @ 15 MV + 1200 MHz @ 5 MV
Purple: 400 MHz @ 15 MV + 800 MHz @ 7.5 MV
Blue: 400 MHz @ 15 MV + 1200 MHz @ 3 MV

For the same bunch length of 1 ns, we have slightly higher bunch emittance with 3 MV at 1.2 GHz (2.3 eVs) than with the 400 MHz alone (2.2 eVs), the bucket area also increasing. In the same way the ΔE/E in the bunch increases from 2.0 x 10^{-4} to 2.2 x 10^{-4}. This latter change is good for IBS.

V_{rf} [MV] @			f_s	$\Delta\omega_s/\omega_s$ @ 1ns	ΔE/E @1 ns 10^{-3}	Relative stability gain	Emittance @ 1ns [eVs]
0.4 GHz	0.8 GHz	1.2 GHz					
15	0	0	22.2	0.099	0.204	1	2.24
15	7.5	0	31.4	0.232	0.262	3.87	2.78
15	0	5	31.4	0.369	0.230	4.74	2.36
15	0	3	28.1	0.288	0.220	3.38	2.31

Table 1. Frequency and energy spreads for the different configurations.

5. Power considerations and the couplers

The final bunch shortening application for a 1.2 GHz SC RF system or other upgrade scenarios require a high total RF voltage in the presence of a very intense beam – up to 2 times ultimate. The number of cavities necessary will probably depend not on the voltage but on the amount of power that the RF coupler(s) can handle. These couplers, together with the design of the cavities and the higher order mode couplers are the major areas of R&D to be pursued. The required power per cavity is proportional to the voltage in the cavity and the beam current evaluated at the resonant frequency which is itself a function of the beam intensity and the bunch length.

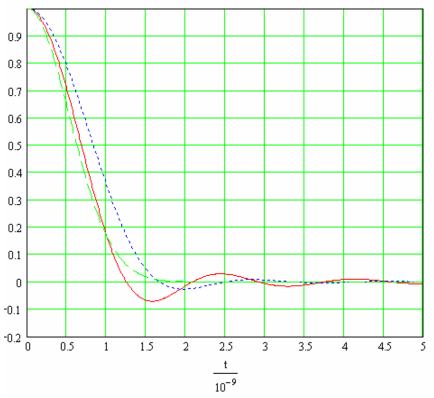

Fig. 2. Normalised spectrum amplitude at 1.2 GHz versus τ (ns) for various line density distributions.
Green: Gaussian. Red: Cos. Blue: Cos^2

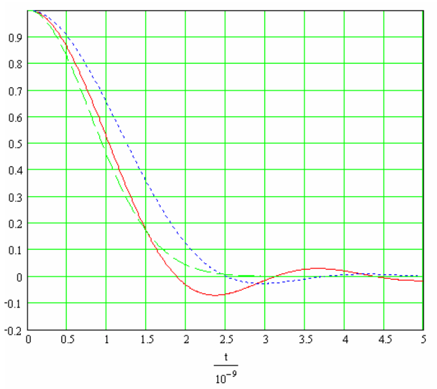

Fig. 3. Normalised spectrum amplitude at 0.8 GHz versus τ (ns) for various line density distributions.
Green: Gaussian. Red: Cos. Blue: Cos^2

Figs. 2 and 3 show the form factors for the two frequencies 1.2 GHz and 0.8 GHz and various distributions in line density. For the Gaussian spectrum the full bunch length τ is taken as $4\tau_{rms}$. The exact distribution will depend on the amount of higher harmonic applied – we will take the higher value for the power calculation as a worst case since in bunch shortening mode there will be an increased component. For a bunch length of 1 (0.5) ns, the values are 0.36 (0.80) at 1.2 GHz and 0.66 (0.90) at 0.8 MHz. For a given cavity voltage the 0.8 GHz power will be 1.8 x (1.1 x) higher than at 1.2 GHz. If we assume that the power required per cavity is given by $V_{rf}\ I_{rf}$ / 8 [12], then the power required for a cavity voltage of 1 MV RF together with the currents for different LHC beams at 1.2 GHz are given in Table 2.

Beam	I_{DC} [A]	Irf [A] at 1.2 GHz	Power [kW] for 1 MV
½ nominal, 1ns	0.29	0.21	26
½ nominal, 0.5 ns	0.29	0.46	58
Nominal, 1ns	0.58	0.42	53
Nominal, 0,5 ns	0.58	0.93	116
Ultimate, 1ns	0.86	0.62	78
Ultimate, 0.5 ns	0.86	1.38	173
2 x ultimate, 1ns	1.72	1.24	155
2 x ultimate, 0.5 ns	1.72	2.75	344

Table 2. Beam current and power required per MV at 1.2 GHz

Experience from other laboratories [13] and also scaling from the 400 MHz LHC acceleration cavity coupler suggests that a 50 kW coupler at 1.2 GHz can be made now. A vigorous R&D programme could aim at a coupler for 200 kW. This would cover the needs to ultimate beam if 1 MV per cavity is assumed. For higher intensities if the power cannot be raised to 350 kW then it would be necessary to reduce the voltage per cavity and increase the number of cavities. With a coupler capable of 120 kW, a Landau damping cavity scheme at 3 MV, i.e. 3 cavities per beam, would operate up to nominal, even with short bunches.

Conclusion

The installation of a higher harmonic RF system into each ring of the LHC would allow a significant increase in instability threshold to be attained even at modest voltages and RF power. As well as providing a means to combat instabilities excited by the presence of unexpected machine impedances it would also allow more freedom in the choice of longitudinal beam parameters. For example it could be possible to reduce the longitudinal emittance of the bunches at 7 TeV giving shorter bunches and more luminosity provided the IBS lifetime remains sufficiently long. Detailed scenarios using such a system remain to be studied but the advantages already cited are evident. If an R&D programme is launched to develop a 1.2 GHz bunch shortening system for the LHC upgrade then it should be possible to produce two prototype cryostats, each with 3 cavities, to be installed in the LHC as a Landau damping system. Even outside the context of a future bunch shortening project, the advantages of such a Landau system, at a frequency to be more carefully studied taking into account all hardware and beam dynamics parameters, suggest an R & D programme would be well worthwhile.

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