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Review of Coupled Bunch Instabilities in the LHC

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Abstract

In order to reach the required luminosity, the LHC will have a large number of high intensity bunches. Coupled bunch instabilities can therefore be excited by the higher order modes (HOMs) of the RF cavities, by parasitic cavities and by the transverse resistive wall effect. This report summarises the growth times of the coupled bunch instabilities taking into account the HOMs (damped or undamped) relevant for the 200 MHz normal conducting cavities, the 400 MHz superconducting cavities, as well as other parasitic cavities. It is shown that, with the damped HOMs of the RF cavities, the coupled bunch instabilities remain within control for the LHC operation. As far as the transverse resistive wall effect at injection is concerned, it is demonstrated that the corresponding growth times can be safely compensated by the proposed transverse feedback system [1].

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1 Introduction

The LHC will be operated with a total of 2808 bunches per beam and with a bunch separation of 25 nsec. With the proposed bunch intensities (1.1×10^{11} for nominal operation and 1.7×10^{11} for the ultimate case), the wake fields generated by a bunch in narrow band structures such as RF cavities, other parasitic cavities and the transverse resistive wall effect will last long enough to affect consecutive bunches and thus potentially lead to coupled bunch instabilities.

The LHC will have two (four cells) superconducting cavities per beam operating at 400 MHz and four normal conducting cavities operating at 200 MHz for efficient injection capture. The interaction of the bunches with these cavities can lead to coupled bunch instabilities (CBI) in the longitudinal as well as in the transverse planes in case the wake fields are strong enough. This problem is potentially more severe in the longitudinal plane as there will be no longitudinal feedback in the LHC [2]. In the transverse planes, there is a feedback system and it is necessary to confirm that the growth times of the CBI are slow enough to stay within the power and gain limits of the feedback system. It is worth underlining that an active feedback operating up to 20 MHz will be able to treat each bunch separately on its fundamental dipole mode, while the higher order bunch oscillation modes will have to be stabilised by Landau damping. Similarly, the feedback system will also be required to ensure a sufficient margin for the control of the transverse emittances.

In a first step, the growth times for each individual type of cavities are evaluated both for the damped and undamped higher order modes. This stresses the importance of the 200 MHz cavities in terms of CBI, but also confirms that the situation remains under control, provided the cavities' HOMs are damped. As far as the present evaluation is concerned, a few additional comments concerning the scenarios included in the study are as follows:

- Although the 200 MHz cavities will be parked after injection, they physically remain in the machine so that their impedance has to be included both for the injection and physics conditions. The same argument applies for the 400 MHz cavities at injection.
- Presently there exists a possibility that the 200 MHz cavities will not be initially installed in the machine (injection being carried out with the 400 MHz cavities at 8 MV). This option has also been included in the study, in order to check that this operation scenario is also safe in terms of CBI.
- Although, during the design phase, a special effort was made to avoid any unnecessary parasitic cavities, there are inevitably some elements in the machine with undesired trapped modes. This is the case for the transverse dampers and for the CMS experimental chamber. Consequently, these elements have been included.
- A lot of work has been done in the past to study the CBI in the LHC [3–7]. The published results illustrate the evolution of the design for many components. A special effort has been made to use the most recent available data for this study. This is particularly true for the compilation of the HOMs of the different elements.
- The LHC filling pattern is not symmetric but is composed by more or less symmetric batches. Unfortunately, most of the standard computational codes available for CBI calculations require a symmetric filling of the buckets. It is therefore assumed that the bunches are symmetrically placed and the calculations are done for the ultimate intensity. Since it has been reported earlier [6, 8, 9] that the maximum growth rate of a non-symmetrically filled ring is always smaller than that of the corresponding

symmetric filling, the estimates using symmetric filling and the ultimate intensity guarantee a safe prediction of an upper bound for the growth rates.

– The transverse resistive wall effect can also couple the motion of different bunches. The transverse resistive wall estimates are rather complicated in the LHC due to different designs of the superconducting, warm, injection and interaction regions. It will be shown that the proposed transverse feedback system can cope with the estimated growth times.

2 Longitudinal Symmetric Coupled Bunch Instabilities

Two mode numbers 's' and 'a' describe a longitudinal coupled bunch mode. For 'k' bunches in the machine, there are 'k' coupled bunch modes characterised by a longitudinal mode number 's' which takes the values; s=0,1,2,.....(k-1), and defines the phase shift

$$\Delta\phi = \frac{2\pi.s}{k}$$

between the bunches. An index 'a' describes the individual bunch motion for each coupled bunch oscillation mode 's'. Thus a=1 is the dipole mode where the bunches move rigidly as they execute longitudinal synchrotron oscillations, a=2 is the quadrupole mode, where the head and tail of the bunch oscillate longitudinally out of phase etc.

The unpertubed modes have frequencies given by

$$\omega_p^{\|} = (pk + s + aQ_s)\omega_0$$

where p=0,±1,±2..., Q_s is the synchrotron tune and ω_0 is the angular revolution frequency.

In the presence of the machine impedance, there is a coherent frequency shift. The coherent frequency shift in the Sacherer-Zotter formalism is given by [10, 11]:

$$\Delta\omega_{s,a}^{\|} = i(\frac{a}{a+1})\frac{I_b\omega_0^2\eta}{3(L/2\pi R)^3 2\pi\beta^2(E_T/e)\omega_s}[\frac{Z_{\|}}{n}]_{eff}^{s,a}$$

where L is the total bunch length equal to $2\sqrt{2}\sigma_l$ (σ_l = rms bunch length) for a parabolic bunch and $2\sqrt{\pi}\sigma_l$ for a Gaussian bunch. R is the average machine radius, I_b is the average bunch current, η is the phase slip factor, E_T is the total beam energy, β is the relativistic beta factor and ω_s is the angular synchrotron frequency=$Q_s\omega_0$. The effective longitudinal impedance is defined by:

$$[\frac{Z_{\|}}{n}]_{eff}^{s,a} = \frac{\sum_{p=-\infty}^{p=+\infty}\frac{Z_{\|}(\omega_p^{\|})}{(\omega_p^{\|}/\omega_0)}h_a(\omega_p^{\|})}{\sum_{p=-\infty}^{p=+\infty}h_a(\omega_p^{\|})},$$

Where $h_a(\omega_p^{\|})$ denotes the bunch mode spectrum characteristic of the synchrotron mode 'a'.

The real part of the coherent frequency shift gives the real coherent mode frequency shift and the imaginary part yields the instability growth rate.

The growth times of the longitudinal CBI have been calculated considering the LHC parameters presented in Table 1. In case the 200 MHz cavities would not be available at injection, the corresponding parameters for injecting into the 400 MHz system are indicated in parantheses.

Ring Circumference [m], C	26658.883	
Number of protons per bunch, N_p	1.1x10^{11} (nominal)	
	1.7x10^{11} (ultimate)	
Circulating beam current [A], I_0	0.706 (nominal)	
	1.091(ultimate)	
Momentum compaction, α	0.000347	
Betatron tunes (H/V), Q_T	63.28/63.31	
Energy [GeV], E_T	450	7000
RF frequency [MHz], f_{RF}	200.35 (400.789)	400.79
Harmonic number, h	17820 (35640)	35640
Number of symmetric bunches, k	3564	3564
RF voltage [MV], V_{RF}	3 (8)	16
rms bunch length [cm], σ_l	17.5 (11.6)	7.73
rms energy spread, σ_E/E	3.06 x10^{-4} (4.68 x10^{-4})	1.11x10^{-4}
Synchrotron tune, Q_s	0.002546 (0.005878)	0.00212
Synchrotron frequency [Hz], f_s	28.64 (66.08)	23.86

Table 1: Parameters of LHC used for CBI estimates

2.1 Longitudinal CBI estimates for HOMs of the 200 MHz cavities

The undamped monopole modes of the 200 MHz capture cavities are given in Table 2 while the damped monopole modes data are given in Table 3 (with 2 HOM couplers and with 4 HOM couplers) [12]. The corresponding shunt impedances are illustrated in Figures 1 and 2. The quoted HOM values apply for one cavity and the shunt impedances are multiplied by the number of cavities (i.e. 4) for growth time estimates.
Using these modes, the growth times of the coupled bunch instabilities have been estimated mainly using the computer program ZAP [11] (the comparison of ZAP with the other codes is given in Ref. [13]). Though the experimental observations on SPS fit quite well with a Gaussian distribution, both parabolic and Gaussian distributions have been considered. It is recalled that the growth times are evaluated for the ultimate LHC intensity.

The CBI are counteracted by Landau damping from the synchrotron frequency spread within the bunches. A spread in synchrotron frequency arises from the non-linearity of the RF bucket. The CBI mode is Landau damped if the shifted mode frequency lies within the effective spread of the bunch. In the different Tables, the flag 'Damped' indicates that the mode is actually 'Landau damped'.

As can be seen from Table 4, with the undamped HOMs of the 200 MHz cavities, the growth times are very fast. The dangerous HOMs are mainly at 245.7, 487.5, 631.1,

Frequency	Rs	Q	Frequency	Rs	Q
(MHz)	(MΩ)		(MHz)	(MΩ)	
245.0	0.103	33400	1556.0	0.002	118200
487.5	1.047	57470	1596.0	0.029	70580
631.1	0.132	49490	1653.0	0.009	102900
716.2	0.731	60000	1672.0	0.221	67680
748.9	0.367	53260	1678.0	0.003	151200
943.6	0.685	88480	1788.0	0.007	100100
1015.0	0.023	79100	1810.0	0.050	62940
1101.0	0.736	72080	1836.0	0.102	76180
1111.0	0.001	62080	1986.0	0.018	81090
1279.0	0.021	61940	2027.0	0.167	71670
1283.0	0.155	98680	2086.0	0.085	66110
1336.0	0.116	83310	2238.0	0.064	81580
1380.0	0.003	84860	2299.0	0.495	37990
1382.0	0.010	71680	2317.0	0.162	60440
1438.0	0.106	66310	2321.0	0.169	60800
1485.0	0.010	82730	2535.0	0.044	62390
1489.0	0.340	75160	2617.0	0.005	55560
1531.0	0.001	108800	2623.0	0.563	56040
1528.0	0.010	86690			

Table 2: Undamped monopole modes of the 200 MHz cavity [12]

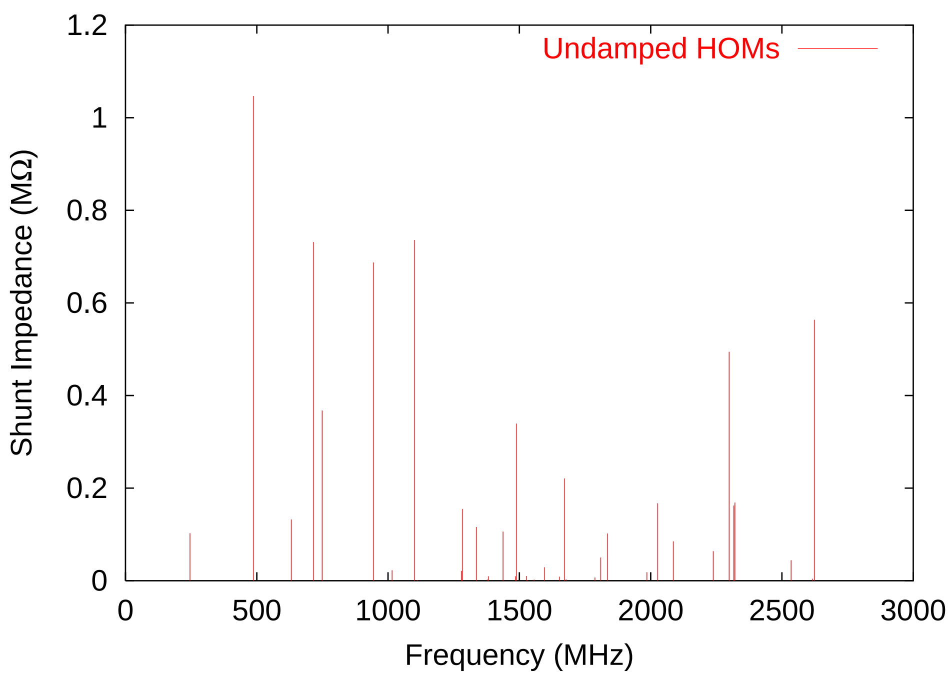

Figure 1: Undamped monopole modes of the 200 MHz cavity [12]

	2 Couplers		4 Couplers	
Frequency	Rs	Q	Rs	Q
(MHz)	(kΩ))		(kΩ)	
245.7	5.063	1645	2.595	843
486.7	6.722	369	3.37	185
633.1	4.338	1622	2.205	824
717.7	4.337	356	2.175	178
751.2	19.430	2817	9.981	1447
946.0	78.860	10191	41.940	5420
1100.0	1.357	4728	0.682	2375
1107.0	91.850	899	48.980	479
1110.0	2.583	113289	1.331	58377
1284.0	3.575	2280	1.951	1244
1335.0	0.613	441	0.307	221
1444.0	1.742	1091	0.878	550
1496.0	49.640	10990	26.780	5929
1603.0	0.862	2083	0.438	1057
1655.0	1.039	12081	0.552	6415
1669.0	8.186	2507	4.170	1277
1814.0	1.178	1482	0.596	750
1834.0	3.392	2533	1.725	1288
1990.0	0.746	3281	0.390	1716
2022.0	6.564	2812	3.348	1434
2088.0	6.662	5180	3.467	2696
2236.0	1.019	1303	0.514	657
2293.0	2.772	213	1.390	107
2326.0	4.695	1692	2.381	858
2521.0	4.193	5922	2.201	3109
2606.0	1.940	23659	1.236	15073
2633.0	2.566	255	1.286	128

Table 3: Damped monopole modes of the 200 MHz cavity [12]

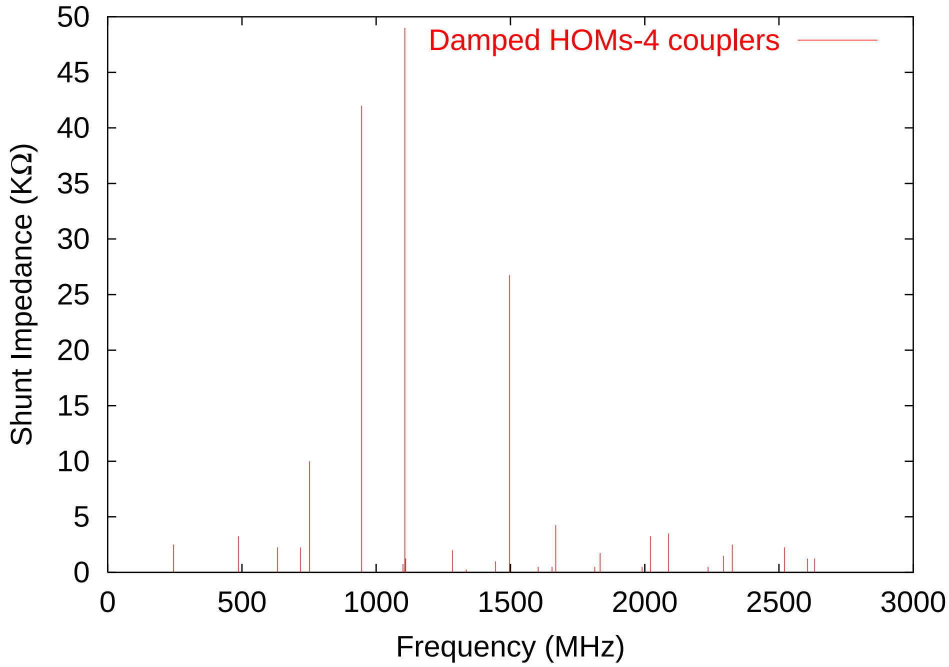

Figure 2: Damped monopole modes of the 200 MHz cavity [12]

Growth Times				
	Parabolic Bunch		Gaussian Bunch	
Bunch mode	Injection	Top	Injection	Top
With Undamped HOMs				
a=1	16 msec	86 msec	53 msec	66 msec
a=2	24 msec	267 msec	19 msec	72 msec
With Damped HOMs 2 Couplers				
a=1	Damped	Damped	Damped	Damped
a=2	238 msec	Damped	Damped	Damped
With Damped HOMs 4 Couplers				
a=1	Damped	Damped	Damped	Damped
a=2	Damped	Damped	Damped	Damped

Table 4: Effect of undamped and damped monopole modes of the 200 MHz cavities

716.2, 943.6 and 1100.99 MHz. As shown in Table 4, the growth time for the bunch mode a=1 at injection energy using parabolic bunch shape is less than that for a=2, but the situation is reversed when a Gaussian bunch shape is used. The growth times are therefore evaluated for both bunch shapes in all cases, to avoid missing the fastest growth time. With 2 couplers on these cavities, as shown in Table 4, all the bunch modes are damped except for a=2 at injection with a parabolic bunch shape. With 4 couplers, all coupled bunch modes are suppressed at injection as well as at top energy.

2.2 Longitudinal CBI estimates for HOMs of the 400 MHz cavities

The undamped and damped monopole modes data for the 400 MHz superconducting cavities [14] are given in Table 5. This data is for one cavity (consisting of 4 cells) and the shunt impedances should be multiplied by the number of cavities per beam (=2). This factor has thus been included in the growth times calculations.

	Undamped HOM		Damped HOM	
Frequency	Rsh	Q	Rsh	Q
(MHz)	(MΩ)		(KΩ)	
779.0	0.301	50000	1.624	270
1184.0	0.068	50000	1.369	1000
1238.0	0.076	50000	0.609	400

Table 5: Undamped and damped monopole modes for the 400 MHz superconducting cavity [14]

Table 6 illustrates the results obtained for the HOMs of the 400 MHz cavities (damped and undamped). The numbers in parantheses correspond to the case where the 400 MHz cavities are used at injection rather than the 200 MHz cavities. With undamped HOMs, the bunch excitation is not suppressed and thus, it is necessary to damp the HOMs with dedicated couplers. With the damped HOMs, the CBI are neither excited at injection nor at top energy.

2.3 Longitudinal CBI estimates for HOMs of Transverse Damper and trapped modes of CMS chamber

The transverse feedback system is composed of 4 dampers per beam. The monopole modes for these dampers have been calculated and measured [15]. The monopole modes for one damper system are given in Table 7. As shown in Table 8, with the undamped monopole modes of the transverse dampers, the bunch motion is unstable (though not very fast) at both energies. However, with the damped monopole modes, all the coupled bunch modes are suppressed at injection as well as top energy.

The detailed design of the CMS experimental chamber is available and the trapped monopole modes have been estimated by Yun Luo [1] using the MAFIA code [16]. The

[1] On leave of absence from IHEP, China

Growth Times				
	Parabolic Bunch		Gaussian Bunch	
Bunch mode	Injection	Top	Injection	Top
With Undamped HOMs				
a=1	0.267 sec	0.403 sec	Damped	0.408 sec
	(Damped)		(Damped)	
a=2	0.116 sec	Damped	Damped	0.290 sec
	(Damped)		(Damped)	
With Damped HOMs				
a=1	Damped	Damped	Damped	Damped
	(Damped)		(Damped)	
a=2	Damped	Damped	Damped	Damped
	(Damped)		(Damped)	

Table 6: Effect of undamped & damped monopole modes of the 400 MHz cavities

	Undamped HOMs		Damped HOMs	
Frequency	Rsh	Q	Rsh	Q
(MHz)	(KΩ)		(KΩ)	
82.8	2.875	820	0.910	260
419.3	26.67	1270	1.785	85
641.2	2.184	1680	0.110	85
880.6	0.816	1020	0.376	470

Table 7: Undamped and damped monopole modes of the Transverse Damper [15]

trapped monopole modes are listed in Table 9. These modes are for half of the chamber, so that the values of the shunt impedances have been multiplied by two for the calculation of the growth times. The monopole mode spectrum for the full chamber is shown in Figure 3. Despite of the numerous modes of this chamber, all the coupled bunch modes remain stable at injection as well as at top energy.

2.4 Summary for the longitudinal plane

The CBI growth times with undamped HOMs of both RF cavities put together alongwith the undamped modes of transverse dampers and the CMS chamber show that the CBI would be excited and thus would not be acceptable for the LHC. However, with the damped HOMs of RF cavities and transverse dampers, the CBI are Landau damped and thus will not be a problem for the LHC operation.

3 Transverse Symmetric Coupled Bunch Instabilities

As described in section 2, the two mode numbers 's' and 'a' are again required to describe a transverse coupled bunch instabilities. The main difference as compared to the longitudinal case is that the index 'a' can take a value equal to zero, meaning that the bunches move rigidly as they execute the transverse oscillations. Thus, a=0, describes the rigid

Growth Times				
	Parabolic Bunch		Gaussian Bunch	
Bunch mode	Injection	Top	Injection	Top
With Undamped HOMs				
a=1	Damped	Damped	Damped	1.32 sec
	(Damped)		(Damped)	
a=2	Damped	Damped	Damped	Damped
	(Damped)		(Damped)	
With Damped HOMs				
a=1	Damped	Damped	Damped	Damped
	(Damped)		(Damped)	
a=2	Damped	Damped	Damped	Damped
	(Damped)		(Damped)	

Table 8: Effect of monopole modes of the Transverse Dampers

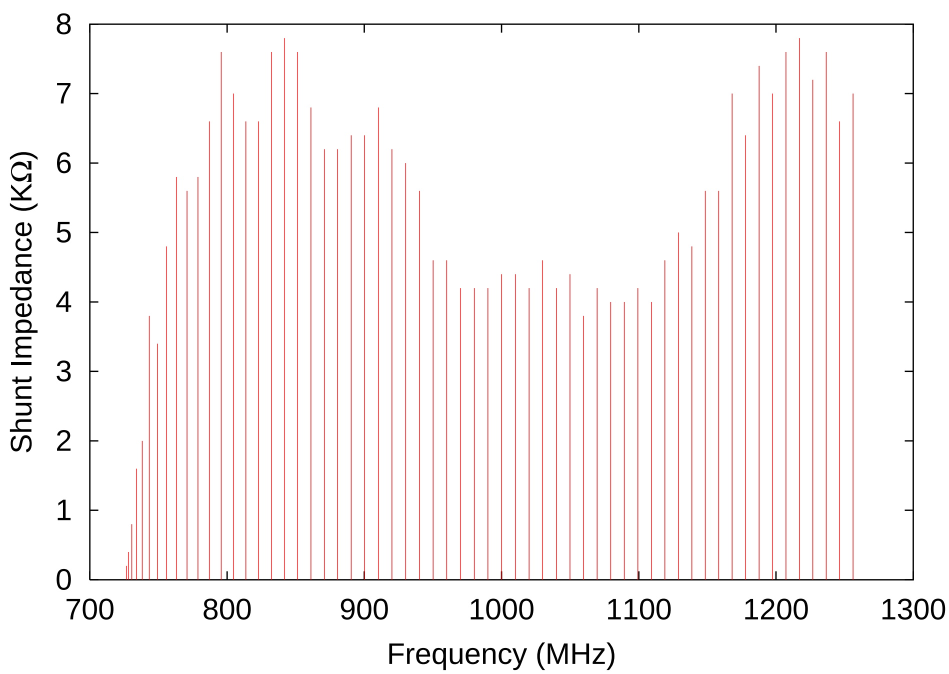

Figure 3: Trapped monopole modes in the CMS chamber

Frequency	Rs	Q	Frequency	Rs	Q
(MHz)	(KΩ)		(MHz)	(KΩ)	
726.6983	0.0288	63884	970.0500	1.0564	66945
728.1463	0.0949	63931	980.0851	1.0514	66964
730.5508	0.2248	64009	990.0418	1.0302	67006
733.8926	0.4158	64118	1000.0659	1.0883	67009
738.1447	0.4754	64255	1009.9896	1.0884	67068
743.2677	0.9347	64417	1020.0383	1.0421	67124
749.2051	0.8326	64600	1029.9429	1.1326	67055
755.8727	1.2044	64792	1039.9324	1.0715	67168
763.1447	1.4392	64973	1049.8354	1.0948	67081
770.8464	1.3979	65122	1059.7559	0.9486	67154
778.8123	1.4366	65241	1069.6556	1.0365	67225
787.0434	1.6605	65392	1079.5973	1.0086	67155
795.6760	1.9059	65585	1089.4116	0.9892	67174
804.6447	1.7380	65723	1099.3186	1.0436	67216
813.6980	1.6601	65787	1109.1486	1.0148	67244
822.8547	1.6683	65924	1119.0148	1.1389	67169
832.2935	1.9124	66078	1128.8116	1.2302	67304
841.8073	1.9299	66110	1138.6862	1.1990	67226
851.3268	1.8895	66223	1148.4681	1.4163	67227
861.0712	1.6847	66359	1158.2424	1.3956	67156
870.8116	1.5260	66347	1168.0477	1.7740	67369
880.5568	1.5502	66471	1177.8507	1.5755	67250
890.4578	1.5880	66543	1187.6633	1.8546	67343
900.2991	1.6098	66574	1197.4185	1.7569	67259
910.2465	1.6903	66688	1207.2347	1.8941	67402
920.1790	1.5731	66674	1217.0260	1.9652	67406
930.1307	1.4848	66794	1226.8158	1.7804	67252
940.1332	1.3889	66792	1236.5526	1.8928	67440
950.0908	1.1274	66855	1246.3333	1.6551	67345
960.0938	1.1384	66859	1256.1288	1.7658	67558

Table 9: Monopole modes in half of the CMS chamber

dipole mode and the mode a=1 applies to the case where the head and the tail of the bunch oscillate transversely out of phase. The frequency of the unperturbed modes in this case is described by,

$$\omega_p^T = (pk + s + Q_T + aQ_s)\omega_0$$

where p=0,±1,±2...and Q_T is the betatron tune. The effective bunch spectrum is modified for the finite chromaticity. The coherent frequency shift in the Sacherer-Zotter formalism is given by [10, 11]:

$$\Delta\omega_{s,a}^T = -i(\frac{1}{a+1})\frac{I_b\beta c^2}{2L(E_T/e)\omega_\beta}[Z_T]_{eff}^{s,a}$$

The effective bunch spectrum is modified for the finite chromaticity as :

$$[Z_T]_{eff}^{s,a} = \frac{\sum\limits_{p=-\infty}^{p=+\infty} Z_T(\omega_p^T)h_a(\omega_p^T - \omega_\xi)}{\sum\limits_{p=-\infty}^{p=+\infty} h_a(\omega_p^T - \omega_\xi)}$$

where ω_β=$Q_T\omega_0$ and ω_ξ is the chromatic frequency given as $\omega_\xi = \xi\omega_0/\eta$ with ξ as the chromaticity.

A complex coherent frequency shift is estimated for the given narrow band impedances in the machine. The real part of the frequency shift gives the frequency shift while the imaginary part gives the instability growth rate.

The transverse rigid dipole mode, a=0, requires in addition to synchrotron spread also a betatron tune spread for Landau damping. However, for modes a>0, synchrotron frequency spread is sufficient to obtain Landau damping. In the Zotter formalism [10], a guess for the betatron tune spread is required as an input for the a=0 mode. The Landau damping condition for a=0 transverse rigid dipole mode with nonlinear betatron tune spread in the Zotter formalism is however not included in ZAP. It has therefore been evaluated with the BBI program.

3.1 Transverse CBI estimates for the HOMs of the 200 MHz cavities

The growth times of transverse CBI have been calculated considering the LHC parameters given in Table 1. The undamped dipole modes of the 200 MHz capture cavities [17] are given in Table 10 and Figure 4. The damped dipole modes are presently not available for these cavities.

The growth times are again evaluated for the ultimate intensity and a corrected chromaticity equal to zero. The growth times in the presence of the undamped dipole modes of the 200 MHz cavities are given in Table 11. The a=0 and a=1 modes show undamped motion. At injection energy, the growth time of the a=0 mode is long enough and can be handled by the transverse feedback. The remaining a=1 mode can be cured by positive chromaticity and by space charge tune spread. At top energy, the space charge tune spread is two orders of magnitude smaller than at injection and will not be sufficient anymore. However, the tune spread arising from beam-beam effect will Landau damp all the coupled bunch instabilities. To guarantee the stability of the beams from injection to top energy, the Landau damping octupoles will be used to provide some tune spread [18,19] and help to stabilise the beam, possibly in conjunction with the feedback system.

Frequency (MHz)	Rs (MΩ/m)	Q	Frequency (MHz)	Rs (MΩ/m)	Q
457.1	16.69	54284	336.7	2.62	47164
599.4	18.01	64817	713.6	3.43	57266
796.2	1.15	44824	801.2	3.40	68352
838.8	1.81	67409	945.3	13.09	63282
857.3	1.80	65143	960.0	1.61	48983
1059.5	3.02	86079	1009.5	6.01	90581
1133.4	0.61	78303	1199.9	14.64	68022
1140.9	0.03	71887	1287.6	0.42	11239
1347.1	1.63	61162	1301.5	1.28	7306
1359.4	0.79	74082	1312.9	0.49	78017
1440.4	3.64	59741	1363.9	2.15	64850
1473.9	0.51	94149	1463.3	0.15	85958
1489.0	1.35	779095	1473.9	0.10	65728
1558.0	0.98	109466	1570.3	2.73	60193
1599.6	1.49	97268	1644.5	0.01	134910
1633.5	0.04	66270	1675.9	0.21	6662
1726.6	4.22	58644			

Table 10: Undamped dipole modes of the 200 MHz cavity [17]

Growth Times				
	Parabolic Bunch		Gaussian Bunch	
Bunch mode	Injection	Top	Injection	Top
a=0	121 msec	522 msec	511 msec	748 msec
a=1	97 msec	Damped	181 msec	Damped

Table 11: Effect of undamped dipole modes of the 200 MHz cavities

3.2 Transverse CBI estimates for the HOMs of the 400 MHz cavities

The undamped and damped dipole modes for 400 MHz superconducting cavities [14] are given in Table 12. In order to convert the R/Q value from the HOM spectrum to the transverse impedance, a tube radius of 15 cm was considered [17]. The estimated growth times in the presence of the undamped and damped HOM of the 400 MHz cavities are shown in Table 13. The CBI growth times are not very fast (a=0 can be handled by the transverse feedback and a=1 is Landau damped) even in the case of the undamped HOMs. The situation is a fortiori even safer with the damped HOMs, since the a=0 mode has very slow growth times and the a=1 mode is Landau damped.

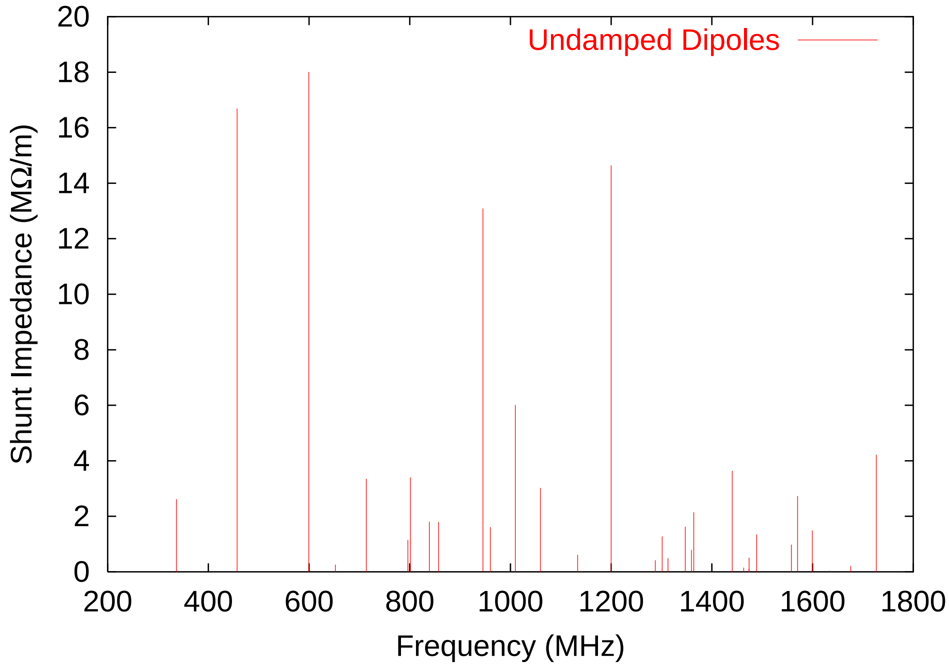

Figure 4: Undamped dipole modes of the 200 MHz cavity [17]

	Undamped HOM		Damped HOM	
Frequency	Rsh	Q	Rsh	Q
(MHz)	(MΩ)		(KΩ)	
500.0	1.76	50000	6.5	137
534.0	5.9	50000	14.0	93

Table 12: Undamped and damped dipoles for the 400 MHz superconducting cavity [14]

Growth Times				
	Parabolic Bunch		Gaussian Bunch	
Bunch mode	Injection	Top	Injection	Top
With Undamped HOMs				
a=0	0.24 sec	2.38 sec	0.547 sec	3.06 sec
	(0.65 sec)		(4.72 sec)	
a=1	Damped	Damped	Damped	Damped
	(Damped)		(Damped)	
With Damped HOMs				
a=0	101 sec	1070 sec	226 sec	1378 sec
	(267 sec)		(1945 sec)	
a=1	Damped	Damped	Damped	Damped
	(Damped)		(Damped)	

Table 13: Effect of undamped and damped dipoles of the 400 MHz cavities

3.3 Transverse Resistive Wall Instabilities

The resistive wall contribution in the LHC is mainly related to the beam screen (the beam screen and the coated copper chambers in the BPMs occupy about 90% of the machine's circumference). The cryogenic part of the beam screen is made of copper cladded stainless steel to keep the resistance as low as possible both for instability and ohmic heating considerations. The resistivity of cold copper is a function of the residual resistance ratio (RRR) and of the magnetic field B. The magnetic field increases the path length of the conduction electrons which leads to a substantial resistance increase at cryogenic temperatures. As for the frequencies around 10 kHz, only 0.3% of the beam image current flows through the stainless steel outside the copper coating, it follows that the surface resistance is almost entirely defined by the thin copper layer. Thus, instead of considering a double layered wall formulation, the impedance of a thin wall is considered [20]. Previous experience with co-laminating stainless steel with copper (thickness 50 micron, with RRR=100) showed that the copper close to the steel gets contaminated (much lower local RRR) during the fabrication process such that the surface impedance is increased. To counteract this effect, it has been decided to increase the thickness of the copper layer from 50 to 75 micron. At injection energy, this design is equivalent to a thickness of 50 microns with an RRR of 100, corresponding to the model used in the present evaluation. However, at top energy, due to the effect of magneto-resistance, the RRR reduces to 30. The transverse resistive wall impedance is calculated as ;

$$R(\omega) = \frac{c\rho l}{\pi t\omega b^3}$$

where, t=thickness of the copper layer, ρ = resistivity of copper at room temperature/RRR, l= total length of the copper coated chamber and b=beam pipe radius.

The relevant parameters used for the calculations of the resistive wall impedances and the growth times are listed in Table 14. The frequency of the lowest dangerous mode is 8 KHz (fractional part of the tune = 0.3). The beta value at the beam screen locations is larger by a factor of 1.3 than the ring average beta values and thus the impedances are scaled up by this factor. The impedance of the warm part of the machine is taken as 20 MΩ/m [21]. Furthermore, the horizontal impedance is taken as 1.4 times smaller than the vertical impedance as dictated by the beam screen geometry [22]. The ring average beta values are taken as the ratio of ring radius to the tune value (=67m). For these estimates, the total intensity is that of 2808 bunches (unlike the number of 3564 symmetric bunches used in the previous sections). As shown in Table 14, the growth time in the vertical plane

Length of the beam screen [Km] including Cu-plated chambers	23.9	
Cu thickness [μm]	75	
Effective Cu thickness [μm]	50	
Vertical radius [m]	0.018	
Frequency of the lowest mode [kHz]	8	
$\beta_{beamscreen}/\beta_{ringaverage}$	1.3	
Vertical/Horizontal Impedance	1.4	
	Injection	Collision
RRR	100	30
Vertical Impedance due to screen [MΩ/m]	36	120
Horizontal Impedance due to screen [MΩ/m]	26	86
Total vertical Impedance [MΩ/m]	56	140
Total Horizontal Impedance [MΩ/m]	46	106
Vertical Growth time [msec] Nominal Intensity [0.56 A] Ultimate Intensity [0.86 A]	 38.6 24.8	 238.6 154.4
Horizontal Growth time [msec] Nominal Intensity [0.56 A] Ultimate Intensity [0.86 A]	 47.0 30.4	 316 205

Table 14: Effect of Transverse Resistive Wall

at injection energy with the present resistive wall impedance is ∼25 msec for the ultimate intensity. This is within the acceptable limits of the transverse feedback (specified to cope up with a growth time of 14 msec [1] for the resistive wall instability). The corresponding growth time at top energy is ∼155 msec. Thus, in the absence of beam-beam tune spread, the transverse oscillations will grow. If the transverse feedback system will be kept on since injection until beams are put into collision, the beam stability will be ensured.

3.4 Summary for the transverse planes

The CBI growth times in the presence of undamped dipole modes of the 200 MHz and damped dipole modes of the 400 MHz cavities can be handled by the transverse dampers. The transverse resistive wall instability growth time at injection energy for the ultimate intensity is within the specifications of the transverse feedback system. However, to ensure the stability of the beam from injection to top energy, the transverse feedback should be kept on until collisions take place.

4 Conclusions

In the presence of the undamped higher order modes of the normal conducting capture cavities (200 MHz) and the superconducting cavities (400 MHz), coupled bunch instabilities are excited in the LHC and the growth times are fast enough to blow up the bunch dimensions and/or cause loss of particles, therefore this would not be acceptable for LHC. Once these HOMs are damped by means of dedicated couplers, the instabilities are Landau damped in the longitudinal plane and the growth times are long enough in the transverse plane so that the excitations can be suppressed by the transverse feedback system. All the higher order coupled bunch modes other than the dipole coupled bunch mode will be Landau damped at injection as well as at top energy. In addition to this, even in the case where the trapped modes of the CMS chamber and the damped modes of the transverse dampers are included, the instabilities thresholds are not exceeded. The coupled bunch instabilities growth times for the initial operation of the LHC with 400 MHz cavities alone (no 200 MHz cavities) also show that the instabilities would be within control.

With the present knowledge of the machine impedance, the resistive wall effect is within control. In the vertical plane, the resistive wall instability growth time at injection is $\sim$25 msec for the ultimate intensity. Nevertheless, it remains true that the impedance of any new component to be installed in the machine has still to be carefully optimized such that the total transverse impedance of the machine remains below 100 MΩ/m at injection. Indeed, this value would correspond to an instability growth time of $\sim$14 msec which happens to be at the limit of what the transverse feedback system could compensate. With the present resistive wall budget, the instability growth time at top energy is $\sim$155 msec. Consequently, in the absence of beam-beam tune spread, the transverse oscillations will grow. It is therefore recommended to keep the transverse feedback system on from injection until beams are put into collision.

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