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COUPLED BUNCH INSTABILITIES IN THE LHC

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In the LHC, the coupled bunch instabilities will be mainly driven by the RF cavities and the resistive wall effect. The growth times of these instabilities have been estimated taking into consideration the undamped and damped higher order modes of these cavities. These estimates show that the rise times of the longitudinal coupled bunch instabilities are under control. The proposed transverse feed-back system allows the same conclusion to be drawn for the transverse resistive wall instability.

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In the LHC, the coupled bunch instabilities will be mainly driven by the RF cavities and the resistive wall effect. The growth times of these instabilities have been estimated taking into consideration the undamped and damped higher order modes of these cavities. These estimates show that the rise times of the longitudinal coupled bunch instabilities are under control. The proposed transverse feedback system allows the same conclusion to be drawn for the transverse resistive wall instability.

1 INTRODUCTION

In the LHC, the coupled bunch instabilities (CBI) can be potentially driven by narrow band structures such as the higher order modes (HOMs) of the RF cavities (both normal and superconducting cavities), other parasitic cavities and the resistive wall effect. 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 LHC will be operated with a total 2808 bunches per beam, with a bunch separation of 25 ns. CBI problems can be more severe in the longitudinal plane since no longitudinal feedback system is foreseen for the LHC [1]. In the transverse planes, there is a feedback system [2], however, it remains necessary to check that the CBI growth times are slow enough to stay within the power and gain limits of the feedback system as well as to ensure a sufficient margin for the control of the emittances.

The CBI growth times have been first evaluated using the undamped modes of the RF cavities. As expected, they lead to CBI in both the longitudinal and transverse planes and thus would not be acceptable for the LHC operation. However, the estimates using the damped HOMs of these cavities confirm that there will be no CBI due to these HOMs.

The resistive wall estimates involve the preliminary knowledge of impedances of the different vacuum chamber geometries and materials. The present approach includes the evaluation of the transverse impedances in both the cold and warm parts of the machine. The different contributions to the impedance budget are discussed and the corresponding instability rise times are presented.

2 ESTIMATES OF CBI DUE TO HOMS

The damped and undamped higher order modes of the RF cavities (normal and superconducting) [3, 4] are used to estimate the growth times of the CBI in the longitudinal and the transverse planes. The additional sources of narrow band impedances are the transverse dampers [5] and the experimental chambers. For the latter, the trapped monopole modes of the CMS experimental chambers have been estimated with the program MAFIA [6] by Yun Luo [1]. Furthermore, the growth times are estimated for the LHC parameters described in Table 1. It should be noted that, although the 200 MHz cavities will be used at injection only, their contribution to the impedance budget has also to be included at top energy. Finally, it is worth mentioning that the code used for the present CBI evaluations requires a symmetric filling of the machine. As a result, we had to use 3564 equally spaced bunches instead of the nominal 2808 LHC bunches. As a consequence, our results are slightly pessimistic. Similarly, both the nominal and ultimate intensities are considered, in order to ensure that the instabilities are under control for all operation scenarios. The growth times are evaluated for the first two lowest order synchrotron modes for both damped and undamped HOMs. All estimates are computed for parabolic and Gaussian bunch shapes with the program ZAP [7].

Table 1: Parameters of LHC used for CBI estimates

Ring Circumference [m]	26658.883	
Bunch population	$1.1\text{x}10^{11}$ (nominal) $1.7\text{x}10^{11}$ (ultimate)	
Total beam current [A]	0.706 (nominal) 1.091(ultimate)	
Momentum compaction	0.000347	
Betatron tunes H/V	63.28/63.31	
Energy [GeV]	450	7000
RF frequency [MHz]	200.35	400.79
Harmonic number	17820	35640
No of symmetric bunches	3564	3564
RF voltage [MV]	3	16
rms bunch length [cm]	17.5	7.73
Rel. rms energy spread	$3.06\ \text{x}10^{-4}$	$1.11\text{x}10^{-4}$
Synchrotron tune	0.002546	0.00212

The corresponding results are presented in Tables 2, 3. The CBI are stabilised by Landau damping from the synchrotron frequency spread within the bunches induced by the non-linearities of the RF bucket. The synchrotron mode is Landau damped if the shifted mode frequency lies within the effective spread of the bunch. In these Tables, the flag ‘D’ indicates that the coupled bunch mode is ‘Landau damped’. In the transverse plane, the a=0 transverse rigid coupled bunch mode 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. As reported in Ta-

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ble 2, the growth times in the longitudinal plane in the presence of undamped HOMs of 200 MHz cavities are very fast and lead to CBI. In the case of the damped HOMs of 200 MHz, 400 MHz, transverse dampers and the experimental chambers, the motion remains stable and hence this case is not included in Table 2.

Table 2: CBI in the longitudinal plane with undamped HOMs for 200 MHz, 400 MHz and transverse dampers

Growth Times				
	Parabolic		Gaussian	
Bunch mode	Injection	Top	Injection	Top
200 MHz cavities - Undamped HOMs				
a=1	16 ms	86 ms	53 ms	66 ms
a=2	24 ms	267	19 ms	72 ms
400 MHz cavities - Undamped HOMs				
a=1	0.27 s	0.40 s	D	0.41 s
a=2	0.12 s	D	D	0.29
Transverse dampers - Undamped HOMs				
a=1	D	D	D	1.32 s
a=2	D	D	D	D

Table 3: CBI in the transverse plane

Growth Times				
	Parabolic		Gaussian	
Bunch mode	Injection	Top	Injection	Top
200 MHz cavities - Undamped HOMs				
a=0	121 ms	522 ms	511 ms	748 ms
a=1	97 ms	D	181 ms	D
400 MHz cavities - Undamped HOMs				
a=0	0.24 s	2.38 s	0.547	3.06 s
a=1	0.65 s	D	D	D
400 MHz cavities - Damped HOMs				
a=0	101 s	1070 s	226 s	1378 s
a=1	D	D	D	D

As shown in Table 3, the mode a=0 is not Landau damped. However, this mode can be handled by the transverse feedback. The remaining a=1 mode due to undamped HOMs of 200 MHz cavities can be cured by positive chromaticity.

There is presently a possibility that the 200 MHz cavities may not be installed initially in the LHC so that the injection would be carried out with the 400 MHz cavities operating at 8 MV. This option would therefore remove the problem of the HOMs for the 200 MHz cavities. For the sake of completeness, the CBI growth times have been recomputed, to confirm that this option also yields stable operating conditions.

3 TRANSVERSE RESISTIVE WALL

In the LHC, about 90$\%$ of the circumference will be maintained at 5 to 20 K while the remaining 10$\%$ of the circumference will be at room temperature. The cryogenic part of the LHC beam pipe (mainly beam screen) will be copper cladded stainless steel to keep the resistance as low as possible both for instability and ohmic heating considerations. The resistivity of the 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. The final resistivity depends thus more on the field than on the RRR for very high magnetic fields. Past experience with co-laminating stainless steel with copper showed that the copper close to the steel gets contaminated during the fabrication process such that the surface impedance is increased.The increase of the resistance has been compensated by increasing the thickness of the copper from 50 to 75μ. The equivalent thickness and RRR turn out to be 50μ and 100 respectively at low B whereas the RRR reduces to 30 at high B.

Table 4 gives the values of the transverse resistive wall impedance for the different components of the LHC. These estimates include the effect of the inductive by-pass, the Yokoya factor [9] and the first slow wave is assumed to be at 8 kHz. The contributions of higher harmonics of 40 MHz of the fundamental slow wave have been taken into account for the kickers, the TDI and the primary vertical collimators. The collimators considered here are only two sets of primary collimators that might be made of carbon and thus would contribute to the transverse impedance. The contribution of the (numerous) remaining collimators made of good conducting material is negligible. The MQW and MBW are special types of magnets in the cleaning insertions. The TDI is a special “collimator” to be used for protecting the machine from a potential misfiring of the injection kickers. Interconnects are the assemblies that contain the shielded bellows. $\beta/<\beta>$ is the beta factor, which gives the weighting factor for the transverse impedance, since the average $<\beta>$ has been assumed to be 70m. The longitudinal surface impedance Z_s is evaluated first. Then, including the Yokoya factor (for non-cylindrical components) and beta weighting factor, it is possible to obtain the transverse impedance from the simple relation:

$$Z_T = \frac{2c}{\omega}\frac{1}{b^2}(\frac{Z_s l}{2\pi b})$$

where ω is the slow wave frequency, c is velocity of light, b and l are the inner radius and the length of the vacuum chamber, respectively. With these values, the growth times and the tune shifts have been estimated for both injection and top energy. The corresponding results are presented in Table 5. As can be seen from it, the fastest growth time is 23 ms in the vertical plane at injection energy, which can be handled by the transverse feedback system. It is foreseen to keep the feedback on throughout the acceleration cycle. Once in collision, the beam-beam effect will provide enough tune spread for Landau damping. It is interesting to observe that the tune shifts related to the resistive wall are small.

Table 4: Resistive wall transverse impedances at 8 kHz

Element	**Length (m)**	$\mathbf{Z}_s (\mu\Omega)$		**b (m)**	$\frac{\beta}{<\beta>}$	$\mathbf{Z}_\perp$**(MΩ/m)**	
		Low B	High B			Low B	High B
Beam screen-H	23600	3.5+1j	10+1j	0.022	1.25	21.4+6.3j	61.0+7.2j
Beam screen-V	23600	3.5+1j	10+1j	0.018	1.25	29.5+8.6j	84.4+9.9j
Interconnect[8]	340	70		0.022	1.25	5.3+0.5j	
Cold-warm transition	10	360+3j		0.022	1.25	0.6+0.3j	
Warm pipe(pipe+etc)	2300	23+18j		0.04	2.2	3.5+2.9j	
MQW(0.2mm Cu)	160	75+6j		0.019	2.9	7.5+1.6j	
MBW(0.2mm Cu)	72	75+6j		0.022	2.0	1.2+0.3j	
TDI-H	2.8				1.6	2.2+4.5j	
TDI-V	2.8	81+2760j		0.005	0.5	1.4+2.8j	
Collimator-H	1.5			0.008/0.0025	1.3	0.3+0.5j	2.2+7.2j
Collimator-V	1.5	177+177j		0.008/0.0025	2.3	1.1+1.6j	7.9+25.4j
Injection-Septum-H	22	60+6j		0.022	1.1	0.3	
Injection-Septum-V	22				2.0	0.5+0.1j	
Dump-Septum	72	60+6j		0.025	2.6	1.3+0.2j	
Injection-Kicker-H	15	6800+1j		0.019	1.6	0.4+4.0j	
Dump-kicker-V	22.5	3400+3600j		0.029	5.2	5.0+8.7j	
Aperture-Kicker-H	1.5	3400+3600j		0.029	3.6	0.2+0.4j	
Total-H						45+21j	84+25j
Total-V						57+28j	118+50j

Table 5: Effect of Resistive wall

	Growth Times		Tune Shifts	
	Injection	Top	Injection	Top
	(ms)	(ms)		
H-plane	29.5	246	0.00022	0.000017
V-plane	23.3	175	0.00030	0.000034

4 CONCLUSIONS

In the LHC, the coupled bunch instabilities can be driven by undamped higher order modes of the RF cavities, by parasitic cavities and by the transverse resistive wall effect. The growth times of the coupled bunch instabilities in the presence of undamped higher order modes are fast enough to blow up the bunch dimensions and/or cause the loss of particles and thus would not be acceptable for the LHC. However, with damped HOMs, the coupled bunch instabilities are Landau damped in the longitudinal plane and in the transverse plane, the growth times are long enough so that the excitations can be compensated by the transverse feedback.

The transverse resistive wall impedance has been estimated for nearly the whole machine. The major contribution to the impedance comes from the beam screen and some other critical components in the warm parts. The resistive wall impedance budget is within the maximum tolerable impedance of 100 $\mathrm{M}\Omega/\mathrm{m}$ [10]. The growth time of the transverse resistive wall instabilities can be handled by the transverse feedback at injection energy while the beam beam induced tune spread will help to Landau damp the beams in collision. Furthermore, the tune shifts associated with the resistive wall effect are small and almost negligible.

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