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INTERMEDIATE REVIEW OF SINGLE BUNCH COLLECTIVE EFFECTS IN THE LHC

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Abstract

This paper presents an intermediate review of the single bunch collective effects in the LHC. It first reviews the LHC impedance budget including all elements for which a design is presently available. Then, based on this updated budget, the corresponding rise times and thresholds for single bunch instabilities are evaluated and discussed.

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1 INTRODUCTION

The last review of the LHC collective effects dates back from 1995 [1]. Although detailed in his content, this review was mainly based on educated guesses, since the design of most of the components were not readily available. Despite of that, the review was a fundamental contribution, confirming that, provided the impedance could be kept within the estimations, the LHC could be safely operated from a collective effect point of view. As the final design of new elements became available, the corresponding impedances have been re-evaluated either by applying analytical estimations, by RF measurements or by numerical estimation with the MAFIA code [2]. Whenever applicable, the three sets of results have been used such as to cross-check the validity of the results. When this was not possible, then at least two sets of results were used for the evaluation.

As far as collective effects for single bunches are concerned, the main parameters are the inductive impedance (Z/n) in the longitudinal plane and the relatively high frequency (broad-band) impedance in the transverse planes. The transverse low frequency impedance (resistive wall), is more relevant for coupled-bunch instabilities and will not be considered here, however, it is treated in a dedicated companion paper [3].

2 LHC BOUNDARY CONDITIONS

Originally, feedback systems for both the longitudinal and the transverse planes were considered. The longitudinal system was based on 200 MHz cavities, mainly dedicated to damp injection transients but which could also have been used as feedback cavities, albeit at a reduced strength. In the meantime, new 200 MHz cavities have been proposed, and a dedicated study [4] has demonstrated that, considering the constraints to be fulfilled in terms of bandwidth and related power requirements, a longitudinal feedback system for the LHC with the present design would be extremely difficult to realize. However, the analysis of the loss of Landau damping at high energy showed that, even in the absence of longitudinal feedback, a sufficient safety margin is provided for the nominal operating conditions, provided the longitudinal inductive impedance (Z/n) remains smaller than 0.28 Ω. This value thus represents a hard limit for the longitudinal impedance of the LHC machine. In the transverse planes, the main boundary condition is to ensure that the transverse broad-band impedance remains small enough such that the threshold for transverse mode coupling instability is higher than the bunch intensities presently foreseen for the operation of the LHC.

3 THE LHC IMPEDANCE BUDGET

Up to now, the design of about 90 $\%$ of the LHC components has been finalised. As far as the remaining 10 $\%$ are concerned, we shall include estimations which reflect the best of our present understanding.

3.1 Longitudinal Impedance Budget

The different elements included in our analysis to compute the LHC impedance budget can be grouped as follows:

- The LHC beam screen: from a pure layout point of view, with its length of about 24 km, it is clearly the most important component of the machine. However, as far as the longitudinal impedance is concerned, the beam screen contributes only via the numerous holes drilled on its surface. The impedance of these holes has been evaluated according to the theory presented in Ref. [5], inserting the corresponding LHC parameters. This yields an impedance of (Z/n) = 0.017 Ω.
- The 200 MHz RF cavities: these 4 units will be used to accommodate the beam emittance coming from the SPS as well as to damp injection errors. With an estimated (R_{shunt}/Q) of 192 Ω per unit, this yields an impedance of about 0.045 Ω for the 4 units. Actually, the effective impedance is expected to be smaller than this value. For this reason, the value included in the impedance budget amounts only to 30 $\%$ of that, i.e. 0.015 Ω.
- The 400 MHz RF cavities: these 8 units compose the core of the LHC RF system. With a (R_{shunt}/Q) of 44.5 Ω per unit, this corresponds to an effective impedance of 0.01 Ω.
- The experimental chambers: the respective contributions vary a lot, due to the very different design. In

terms of impedance, ATLAS is rather optimal, with a very smooth vacuum chamber. Its contribution is therefore negligible. The design of CMS is well advanced and its contribution has been estimated to 0.0005 Ω for the experiment. TOTEM, when operating (i.e. in closed position) should increase the contribution by about the same amount, namely 0.0006 Ω. For ALICE, the final design is not yet available, but the present estimation amounts to 0.001 Ω. Finally, the contribution from LHCb is by far the most important, amounting to 0.0085 Ω (of which more than 80 % are due to the vertex detector in closed position).

- The shielded bellows: due to the very high number of these elements, the design phase was particularly critical. As a result of an intense and successful optimisation campaign, the impedance of the 1700 shielded bellows could be kept as low as 0.01 Ω.
- The unshielded bellows: such elements are extremely unfavourable from an impedance point of view, and a special effort was made to avoid such components whenever possible. As a result, their number could be restricted to a few elements in the surroundings of the LHC experiments. Their total length is expected to be around 3 m, with an impedance of 0.005 Ω.
- The vacuum valves: another element whose occurrence in the machine is high. The valves with an inner radius of 31.5 mm will be connected to the normal vacuum chamber (radius of 40 mm) by two tapers with a slope of 15 degrees. For 350 units per ring, this yields an impedance of 0.005 Ω.
- The Beam Position Monitors (BPMs): there are basically three different types of monitors in the LHC, namely the button electrodes monitors which are installed in the arcs of the machine and are thus by far the most numerous, some strip lines monitors installed in the warm parts of the machine and finally some ”hybrid” monitors (combination of strip lines and buttons) also foreseen for the straight sections. In total, there will be more than 500 BPMs per ring, with an impedance estimated to be 0.002 Ω.
- The re-combination chambers: these are special chambers (8 in total) where the beams, which travel in a common vacuum chamber around the experiments, are separated to go in the two separate rings. These chambers required a dedicated optimisation in order to avoid the presence of trapped modes. In total, the re-combination chambers are expected to contribute for 0.001 Ω.
- Special equipment: Special components like the injection and dump kickers, the septa and the TDI are not expected to contribute significantly to the longitudinal impedance budget, since they are equipped with a thin metallic layer on their inner surface.

A few important elements are still missing from this list, namely those for which the conceptual design is still missing. These are essentially the collimators and the special equipment for beam instrumentation. As far as the collimators are concerned, we assumed that i) they will be mounted on the conventional vacuum chamber (radius 40 mm), ii) the inner radius will be around 8 mm at injection and iii) the transitions will be tapered with a slope ranging between 10 - 15 degrees. For 20 collimators, the corresponding impedance is estimated to 0.004 Ω. At this point, it is important to stress that, in case the material retained for these components would be an insulator, then it is mandatory to have a thin metallic layer (a few microns) deposited on the inner surface, in order to guarantee for the low inductance quoted here. Given our present information, a guess for the beam instrumentation is even more difficult. Our present estimation relies on 24 units per ring, with an inner radius of 40 mm, an outer radius of 60 mm and conventional tapers for the connections. Such a system would yield an impedance of about 0.001 Ω.

The longitudinal impedance budget summarising the description given above is presented in Table 1.

Table 1: Estimated impedance budget for the LHC in the longitudinal plane.

Element	Number or length	(Z/n) [mΩ]
Beam screen pumping holes	24 km	17
200 MHz cavities	4	15
400 MHz cavities	8	10
Exp. chambers	5	11
Shielded bellows	1700	10
Unshielded bellows	3 m	5
Vacuum valves	350	5
Collimators	20	4
Beam monitors	500	2
BI instruments	24	1
Re-comb. chambers	8	1
Total		81

As can be seen from Table 1, the total estimated longitudinal impedance is slightly less than the 0.1 Ω defined as the objective two years ago. However, this positive result should not be misinterpreted, in the sense that the quoted impedance budget reflects our estimations, which need to be confirmed once the final equipment becomes available. Consequently, it seems reasonable to assume a value of 0.1 Ω for the evaluation of the longitudinal thresholds for stability.

3.2 Transverse Impedance Budget

It is essential to stress that the transverse impedance budget discussed in this section refers to the broad-band impedance of the machine (relatively high frequency, i.e.

several GHz) and does not include the (low frequency) resistive wall contribution, which is presented in a companion paper [3], since the resistive wall effect is more relevant for coupled-bunch instabilities. Except for the BPMs for which the values are taken from a dedicated evaluation [6], the transverse impedance is derived from the longitudinal values according to the simple relation:

$$Z_T \quad = \quad \frac{2R}{b^2} \times (\frac{Z}{n})$$

where R is the LHC radius and b the inner radius of the vacuum chamber. Furthermore, we shall restrict ourselves to quote the values for the vertical plane, since it is the more critical for the present evaluation. The corresponding results are presented in Table 2.

Table 2: Estimated impedance budget for the LHC in the vertical plane.

Element	Inner radius [mm]	β/β_{av}	Z$_T$ [kΩ/m]
Beam screen pumping holes	18	1.25	500
200 MHz cavities	50	3	155
400 MHz cavities	150	2.9	11
Shielded bellows	20	1.25	265
Vacuum valves	40	1.25	35
Collimators	8	4.3	2300
BPMs [6]	25	1.25	300
BI instruments	40	2.15	12
Total			3578

As can be seen from the Table, the transverse contribution is largely dominated by the elements whose structure is in the direct vicinity of the beams, such as the collimators. Some of the elements contributing in the longitudinal plane, like the re-combination chambers, the unshielded bellows and the experimental chambers have been omitted in this list. Indeed, their contribution is expected to be negligible, mainly because they are located at positions with relatively small beta functions. TOTEM has also been left out, since, at injection, the experiment will not be in closed position. To summarise, the estimated LHC broad-band impedance will be rounded up to 4 MΩ/m. Actually, this value has still to be multiplied by the average beta function β_{av} which had been taken equal to 70 m in the above estimations. This yields a value of 280 MΩ, which will be used for the computation of the instability thresholds.

4 THRESHOLDS FOR INSTABILITIES

For the impedances quoted above, the stability thresholds for the longitudinal microwave instability, the loss of Landau damping in the longitudinal plane and the transverse mode coupling instability (TMCI) have been evaluated both at injection and at top energy. For the sake of simplicity, we shall quote only the lowest threshold obtained in each case. The corresponding thresholds are presented in Table 3.

Table 3: Thresholds of stability (maximum bunch population) for the LHC for both the longitudinal and vertical planes.

	Injection 450 GeV	Injection 450 Gev	Top Energy 7 TeV
RF type [MHz]	200	400	400
RF Volts [MV]	3	8	16
Total bunch length [m]	0.7	0.464	0.3
Sync. tune Q$_s$ [$\times 10^3$]	2.55	5.88	2.12
Worst case	TMCI	TMCI	Landau
N$_b^{th}$ [$\times 10^{-11}$]	7.5	11.5	6.7

These thresholds have to be compared with the bunch intensities foreseen for the operation of the LHC, namely 1.1×10^{11} for the nominal scheme and 1.7×10^{11} for the so-called ultimate configuration. As can be seen from it, a substantial safety margin is provided for all the cases considered.

5 CONCLUSIONS

For the evaluation of single bunch instabilities, the most important ingredients are the longitudinal impedance (Z/n) and the high frequency broad-band transverse impedance. In a first step, the main components contributing to these impedances have been identified, and the corresponding impedance budgets have been established. Based on these budgets, the stability thresholds for the microwave instability, the loss of Landau damping and TMCI have been evaluated and found to be higher than the bunch intensities presently foreseen for LHC operation. From these results, it can be concluded that single bunch effects are not expected to be a problem for the LHC operation.

6 REFERENCES

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