IMPEDANCE STUDIES FOR THE PHASE 2 LHC COLLIMATORS

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Abstract

The LHC phase 2 collimation project aims at gaining a factor ten in cleaning efficiency, robustness and impedance reduction. From the impedance point of view, several ideas emerged during the last year, such as using dielectric collimators, slots or rods in copper plates, or Litz wires. The purpose of this paper is to discuss the possible choices, showing analytical estimates, electromagnetic simulations performed using Maxwell, HFSS and GdFidL, and preliminary bench measurements. The corresponding complex tune shifts are computed for the different cases and compared on the stability diagram defined by the settings of the Landau octupoles available in the LHC at 7 TeV.

INTRODUCTION

The 44 collimators per ring required for the Phase 1 of LHC collimation dominate the total transverse impedance at both injection and top energy after the squeeze, as can be seen in Fig. 1 [1]. If one zooms between 8 kHz (which is the 1st unstable betatron line in the LHC) and 20 MHz (which is the frequency limit of the transverse feedback), it can be observed that the real part of the impedance is almost flat. Indeed, the value of the real part of the impedance at 8 kHz is ~ 141 MΩ/m, while the value at 20 MHz is ~ 55 MΩ/m. The ratio between the two values is only ~ 2.6 (it would have been 50 in the case of the classical resistive-wall theory [1]). This effect could be of importance for the transverse feedback as the gain of the power amplifier usually rolls off rapidly when approaching 20 MHz, but it seems that this is not a major issue and that the transverse feedback can be used even at top energy [2]. The normal operating mode of a feedback is indeed at gains corresponding to 20-40 turns damping and the predicted instability rise-times are much longer than that, as ~ 2000 turns are anticipated [1].

Another worry expressed in the past with the transverse feedback at top energy concerned issues with the noise. However, it was estimated from numerical calculations that it should be possible to run in the LHC at a gain of 0.1 (10 turns damping) with a monitor resolution of 0.6% of rms beam size and still have a luminosity life-time of one day [3]. The corresponding required resolution is 7.2 μm at 450 GeV/c ($\sigma = 1.2$ mm) and

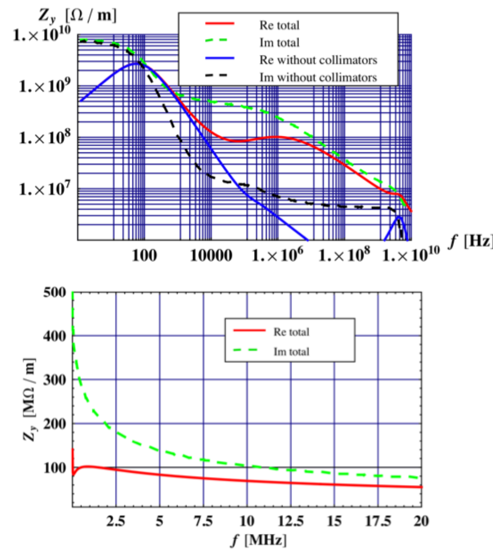

Figure 1: Vertical impedance at top energy after the squeeze (upper). Zoom between 8 kHz (1st unstable betatron line in the LHC) and 20 MHz (frequency limit of the transverse feedback).

1.8 μm at 7 TeV/c (σ is proportional to $\gamma^{-1/2}$). If the gain can be reduced, then the requirement for the monitor resolution can be relaxed.

However, if for one reason or another the feedback system cannot be used, the transverse coupled-bunch instabilities have to be stabilized by Landau octupoles. In this case only about half of the nominal intensity can be stabilized (see Ref. [1] or Fig. 2). As the collimators' impedance imposes a limit on the maximum achievable intensity for Phase 1, the following question is raised for Phase 2: how can we improve the beam stability situation? Some answers were already given in Ref. [1]: (i) the transverse impedance (both real and imaginary parts) of the LHC can be decreased by increasing the gap of the collimators (but there is a trade-off between impedance reduction and cleaning efficiency); (ii) the real part of the transverse impedance of the LHC is increased by reducing the resistivity of the secondary collimators. If one wants to stabilize the beam at top energy by Landau damping, then one should try and reduce the imaginary part of the collimator impedance, as can be seen from Fig. 2. This observation led to the idea of good conductor (copper) collimators. However, if one wants to (can) stabilize the beam at top energy by transverse feedback, then, in this case, one could help the feedback system even more by reducing the real part of the collimator impedance (in particular until ~ 20 MHz). This led to the idea of ceramic collimators.

COPPER SECONDARY COLLIMATOR

The advantages of using copper secondary collimators are twofold: the beam is closer to the stability limit (i.e. it is better for the coupled-bunch instability) even if the imaginary part of the tune shift is increased, and it reduces the imaginary part of the longitudinal and transverse impedances (which is good for single-bunch instabilities as seen in the next section). Furthermore, the feedback should also be able to stabilize the beam in this case. The beam stability situation for Phase 1 and 2 (using copper secondary collimators and cryogenic collimators) is compared in Fig. 2. It should be mentioned that for Phase 2, 17 collimators are added to the 44 collimators of Phase 1 (with some gaps changed) [4]. As with Phase 2 a much better cleaning efficiency is obtained [4,5], this opens up the possibility to open the gaps even further.

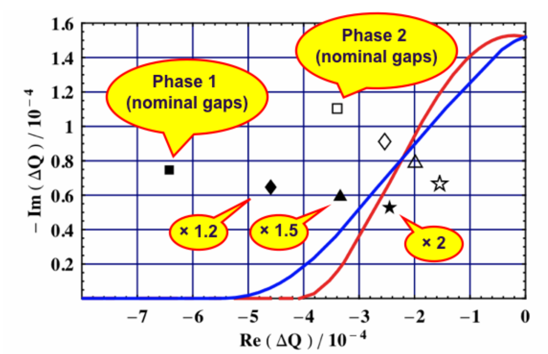

Figure 2: Stability diagram from Landau octupoles (at maximum current) and vertical coherent tune shifts for the LHC at top energy after the squeeze with nominal beam parameters and for both Phase 1 and 2 (with copper secondary collimators and cryogenic collimators [4]). The axes give the real part and minus the imaginary part, respectively, of the coherent tune shift.

CERAMIC SECONDARY COLLIMATOR

Using ceramics, the real part of the impedance (responsible for the instability rise-time) can be considerably reduced (at least at low frequency), as can be seen in Fig. 3, which was produced using analytical formulae [6]. These analytical estimates have been checked with the electromagnetic codes Maxwell, HFSS and GdFidL [7] and most of the time a very good agreement was found [8]. A comparison between HFSS and GdFidL is shown for instance in Fig. 4. Furthermore, some bench measurements were also performed on

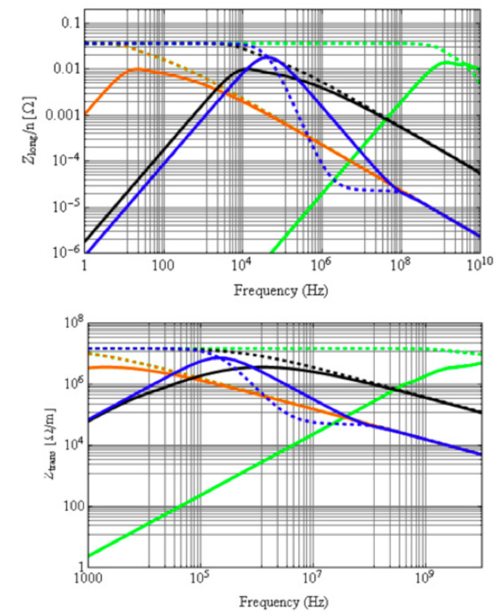

Figure 3: Longitudinal (upper) and transverse (lower) impedance in the case of a round beam pipe with a radius of 2 mm and a length of 1 m: 2.5 cm of copper with vacuum outside (in orange); 2.5 cm of graphite with vacuum outside (in black); 2.5 cm of ceramic (with a real dielectric constant of 5 and a resistivity of 1 Ωm) with vacuum outside (in green); and 10 μm of copper coating on 2.5 cm of ceramic with vacuum outside. The real part is in full line while the imaginary part is in dotted line.

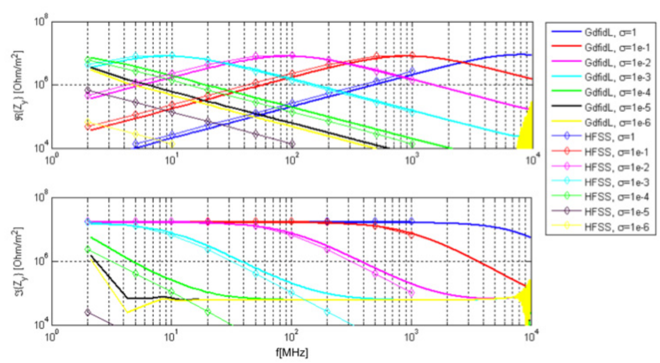

Figure 4: Comparison between GdFidL and HFSS [7] in the case of a round beam pipe with a radius of 2 mm, a length of 1 m, a thickness of 1 cm (with perfect conductor outside), for several values of conductivity: Real (upper) and imaginary (lower) part of the transverse impedance.

copper collimators with rods or slots (and even Litz wires). The idea behind was that the geometry will force the induced currents to move away from the beam and therefore the transverse impedance is expected to be smaller at low frequencies. Indeed, measurements confirmed the expectations at low frequencies [8].

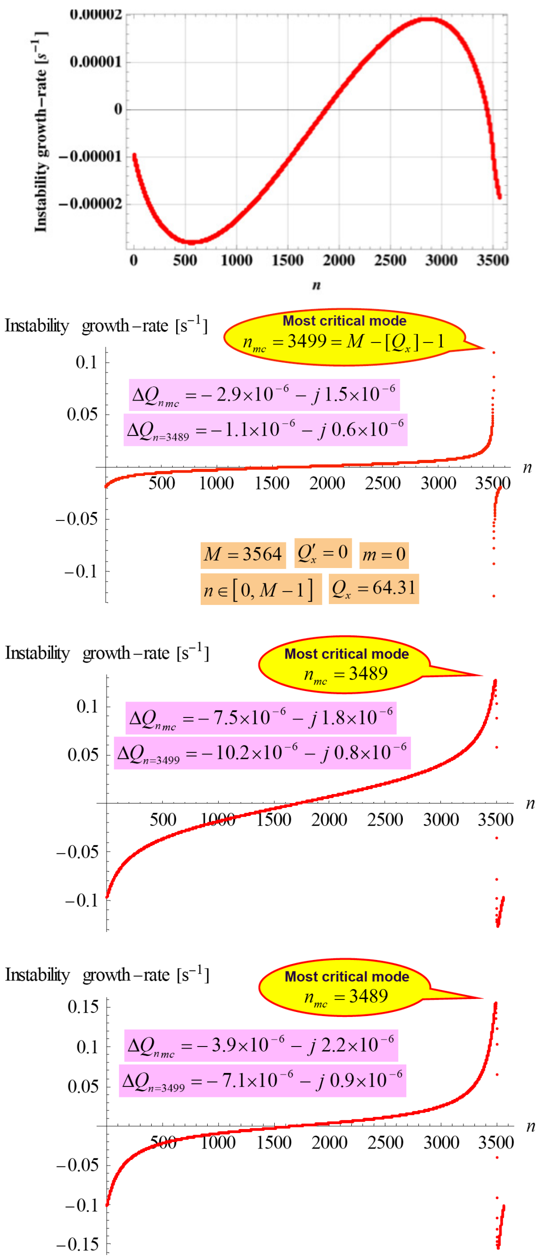

Figure 5: Instability growth-rate vs. the transverse coupled-bunch mode number n for the case of a round beam pipe with a radius of 2 mm and a length of 1 m: ceramic with a real dielectric constant of 5 and a resistivity of 1 Ωm (a), copper (b), graphite (c) and copper coated (with 5 μm) graphite (d). In all cases the thickness is 2.5 cm with vacuum outside.

The instability growth-rate for the case of a ceramic collimator is shown in Fig. 5, and compared to the other cases previously computed. The imaginary part of the tune shift can be deduced from Fig. 5, and is ~ - 2.7 10^{-10}. This value reveals that the effect of the real part of the impedance was considerably reduced. However, the imaginary part of the longitudinal and transverse impedances should also be kept at small values to avoid single-bunch instabilities. In the longitudinal plane, the most critical mechanism is the loss of landau damping for the dipole mode at top energy, which sets a limit for the effective longitudinal impedance $|Z_l(n)/n|$ to ~ 0.6 Ω [9]. The estimated current value is ~ 0.1 Ω [10].

In the transverse plane, the Transverse Mode Coupling Instability, whose lowest threshold is obtained when the single-bunch tune shift of mode 0 is equal to ~ minus the synchrotron tune, sets a limit for the imaginary part of the effective impedance to ~ 134 MΩ/m. The current value is estimated to ~ 30 MΩ/m a top energy with Phase 1.

CONCLUSION

The impedance and associated collective effects were reviewed for the Phase 2 LHC collimators, considering potential candidates such as copper or ceramic jaws.

The use of copper blocks (instead of the long monolithic bars) with small gaps could be very interesting for the mechanical construction. Those gaps possibly covered with a copper foil (spotwelded) on a small retracted indent of ~ 1 mm would keep the geometrical impedance very small.

Several options are discussed for beam stabilization at top energy, such as transverse feedback, Landau damping from octupoles and/or beam-beam tune spread, and non-vanishing chromaticity. However, some of them might lead to beam lifetime issues, which will have to be investigated experimentally. The best way to reduce the collimator impedance remains to open the gaps and reduce the total length. Both aspects could be achieved for instance by using crystals [11].

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