IMPEDANCE MEASUREMENTS AND SIMULATIONS ON THE TCT AND TDI LHC COLLIMATORS

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Abstract

The LHC collimation system is a critical element for the safe operation of the LHC machine and it is subject to continuous performance monitoring, hardware upgrade and optimization. In this work we will address the impact on impedance of the upgrades performed on the injection protection target dump (TDI), where the absorber material has been changed to mitigate the device heating observed in machine operation, and on selected secondary (TCS) and tertiary (TCT) collimators, where beam position monitors (BPM) have been embedded for faster jaw alignment. Concerning the TDI, we will present the RF measurements performed before and after the upgrade, comparing the result to heating and tune shift beam measurements. For the TCTs, we will study how the higher order modes (HOM) introduced by the BPM addition have been cured by means of ferrite placement in the device. The impedance mitigation campaign has been supported by RF measurements whose results are in good agreement with GdfidL and CST simulations. The presence of undamped low frequency modes is proved not to be detrimental to the safe LHC operation.

INTRODUCTION

The work we present[1] describes the upgrade of two important elements in the LHC collimation protection system: the two LHC TDIs (TDI2 in point 2 for beam 1 and TDI8 in point 8 for beam 2) and the TCTs.

In the first part we will present the main changes performed on the TDI absorber jaw to mitigate the beam induced heating from resistive wall impedance. RF measurements have been performed on the new upgraded TDIs and the ones extracted from the machine at the end of 2015: we will show the outcome of the longitudinal and transverse wire impedance measurements and the comparison with observed beam induced heating and tune shift observations.

In the second part we will describe the main changes on the collimators hosting embedded button BPM (mainly TCTs and some secondary collimators). Extensive GdfidL [1] and CST [2] simulations have been run to support the RF measurements whose results are found in good agreement and allowed the safe device installation in the LHC.

TDI

In 2012, during the LHC run I, problems with heating were experienced on the TDI and the Cu beam screen was found to be deformed [3]. It was therefore decided to replace the beam screen with a more robust one made of stainless steel and proceed to the resistive wall impedance reduction of the jaws. These were made of three parts: one made of 6×471 mm long blocks of hexagonal Boron Nitride (hBN) coated with 5μm of Ti, a 600 mm Al block and a 700 mm Cu block.

To meet the requirement of robustness and high surface conductivity, the first part of the jaw has been replaced with graphite SGL 4550 coated with 0.1 μm of Ti for adherence purpose and 2μm of copper, while the second Al block has been coated with 1 μm of Ti and the last one replaced by CuCr1Zr. Few blocks were produced and tested in 2014 with RF loop measurements ensuring a factor $\simeq$ 60 reduction in beam induced heating from resistive wall impedance [4].

In 2015 two spares with the new jaws were produced for the 2016 run. In the meantime performance degradation was again observed during the 2015 run (i.e. with the old TDIs) from heating and transverse stability observables on the TDIs: a factor $\simeq$ 4 higher tune shift and $\simeq$ 2 higher synchronous phase shift in the TDI8 w.r.t. TDI2 were measured [5].

Longitudinal Impedance Measurements

At the end of 2015, during machine technical stop, the two operational TDIs were extracted from the machine and impedance bench measurements were performed on them and on the new TDIs for 2016 run [6]. Figure 1 shows a clear difference between the 2015 TDI8 and TDI2 supported by the observation of a more corrupted coating in TDI8 [7]. A clear improvement, instead, can be seen for the TDIs installed for 2016: the improved coating drastically reduced the longitudinal broadband impedance. On the other hand, the low frequency HOMs are not strongly affected by the jaw upgrade as they are located mainly around the jaws and the beam screen [8].

The measured longitudinal impedance was therefore used to cross check the heating observed during beam measurements. Figure 2 shows the comparison for TDI2 where a very good agreement could be achieved, and TDI8 where a factor $\simeq$ 1.5 out of 2 could be explained, compatible with the 0.01° accuracy achievable in beam measurements.

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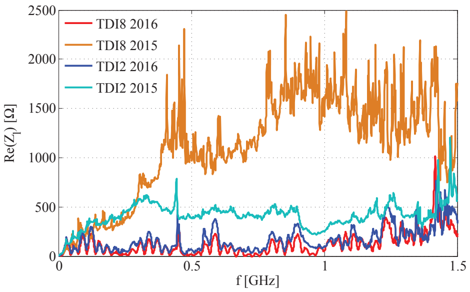

Figure 1: Real part of the longitudinal impedance of the 2015 TDI and the 2016 ones. The impedance is measured with the wire technique at 5mm half gap.

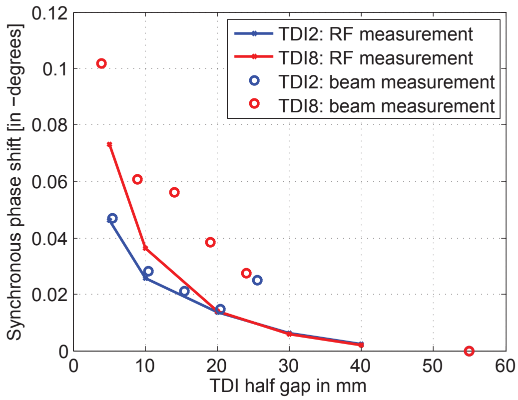

Figure 2: Synchronous phase shift measured with a nominal LHC single bunch and calculated with the measured TDI longitudinal impedance.

Transverse Impedance Measurements

The total (i.e. sum of dipolar and quadrupolar) transverse vertical impedance was as well measured moving the wire perpendicularly to the jaws [9], and added to the LHC injection impedance model. Considering the Sacherer (azimuthal and radial) mode 0 [9] we can calculate the tune shift as a function of chromaticity $\xi = (\Delta Q/Q)\ /\ (\Delta p/p)$ where Q is the tune and p the synchronous particle longitudinal momentum. Varying chromaticity the mode spectrum shift is given by the chromatic frequency $f_\xi = f_{rev} Q\xi/\eta$ [9] where f_{rev} is the LHC revolution frequency and η the slip factor. Each unit of $Q' = Q\xi$ corresponds therefore to $f_\xi \simeq$35 MHz.

Figure 3 shows the expected tune shift as a function of Q'. For operational $Q' \simeq 10$ at injection, a tune shift in TDI8 of a factor $\simeq 4$ higher w.r.t. TDI2 is computed as observed in beam measurements.

TCT WITH EMBEDDED BPMS

During the last LHC long shutdown, two TCS made of CFC and 16 TCT made of Tungsten (W) collimators were replaced by new devices with embedded BPM pickup buttons [10]. The CAD drawing of the new collimator used in our simulations is shown in Fig. 4. With respect to the previous design important changes were made: the lateral RF fingers were removed and HOM damping was entrusted to the TT2-111R ferrite blocks. In order to accommodate the BPM button the jaw tapers were divided in two tapers with a flat central part used for the BPM allocation.

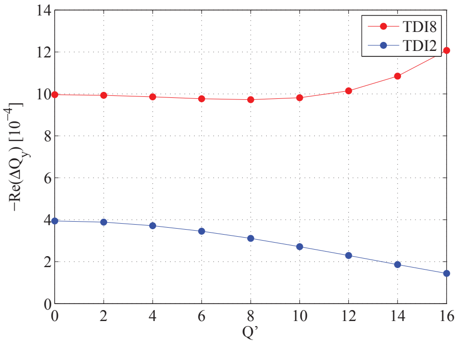

Figure 3: Total TDI tune shift as a function of Q' for a nominal LHC bunch ($N_b = 1.2 \cdot 10^{11}$ ppb intensity and σ_z^{rms} =9 cm bunch length).

Impedance Simulations

We evaluated how these changes affected the transverse broad band impedance comparing the kick factors for the old and new collimators for three different values of the jaws half gap [11]. Table 1 resumes the results: the effective impedance is by about 20% higher for the new collimators mainly due to the steeper tapers in the new collimator jaws.

Table 1: Geometric transverse kick factors for the old and new TCS/TCT geometries, calculated at different half gaps.

	w/ BPM	w/o BPM
Half gaps (mm)	k_T ($\frac{V}{Cm}$)	k_T ($\frac{V}{Cm}$)
1	$3.92 \cdot 10^{14}$	$3.34 \cdot 10^{14}$
3	$6.27 \cdot 10^{13}$	$5.32 \cdot 10^{13}$
5	$2.46 \cdot 10^{13}$	$2.12 \cdot 10^{13}$

In order to study the narrow-band impedance behavior and the effectiveness of the HOM damping with the ferrite blocks, we performed detailed simulations of the real collimator structure accounting for the finite conductivity of the W jaw and the frequency-dependent permeability of the TT2-111R ferrite [12]. In parallel to the GdfidL simulations we used also a CST simplified collimator model to easily perform parametric impedance studies.

As shown in Fig. 4, the TT2-111R ferrite resulted to be very effective in damping the transverse HOMs for frequencies above 500 MHz.

The modes at lower frequencies are less damped. The residual transverse HOM at 82.6 MHz and 167.2 MHz still have non-negligible shunt impedance R_s and have been investigated by RF measurements.

Impedance Measurements

In order to find presence of low frequency HOMs, we used probes with straight and bent extremity, and a loop [13]. The probes ensure a good coupling to the HOM electric field

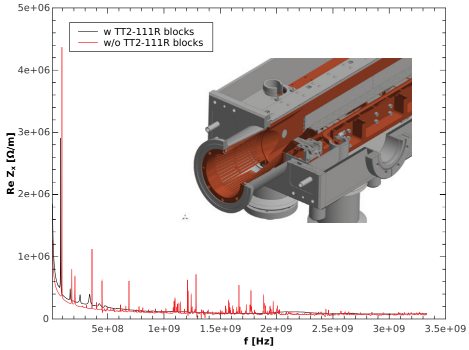

Figure 4: Transverse dipolar impedance of the TCT model calculated with GdfidL, for 3 mm half gap, with and without TT2-111R ferrite blocks.

while the loop couples mainly to the magnetic field. Figure 5 shows the comparison of the three methods: we conclude that the probes cannot excite well the low frequency modes that are instead clearly visible using the loop excitation at 87 and 169 MHz as predicted by the GdfidL simulations.

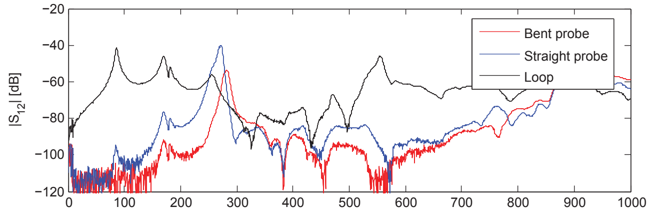

Figure 5: Transmission scattering parameter $S_{2,1}$ measured with straight and bent probes and with a loop.

The unloaded Q, similar for the two low frequency modes, was measured as $Q \simeq 20$ in transmission ensuring low coupling of the loops for different jaw gap positions.

In order to evaluate the R_s, wire measurements were performed displacing horizontally the wire in steps of 0.25 mm for 5, 10 and 15 mm half gaps. A good agreement with GdfidL and CST simulations is obtained as shown in Fig. 6 for the 87 MHz mode.

In order to estimate the effect of the low frequency HOMs, DELPHI simulations were performed [14, 15] both in single and coupled bunch regime at $Q' = 5$ with a 50 turns transverse damper. Figure 7 shows the effect of an additional HOM of variable resonant frequency f, $Q = 20$, and $R_s \in (1, 10, 100)$ MΩ/m on the transverse LHC growth rate of the most unstable coupled bunch mode: being in the range of 1MΩ/m, the HOMs introduced by the TCTs are not expected to be an issue for the LHC beam stability. Similar conclusions hold for the single bunch case.

CONCLUSIONS

In this work we collected the main results concerning the impedance simulations and measurements performed on the TDI and the TCTs.

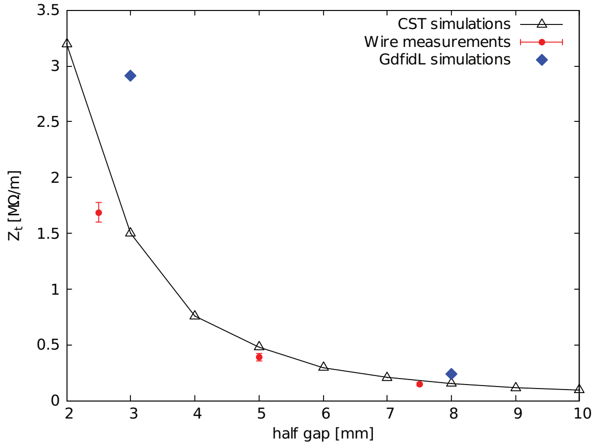

Figure 6: Shunt impedance R_s of the 87 MHz mode versus half gap as measured with wire and simulated in CST and GdfidL.

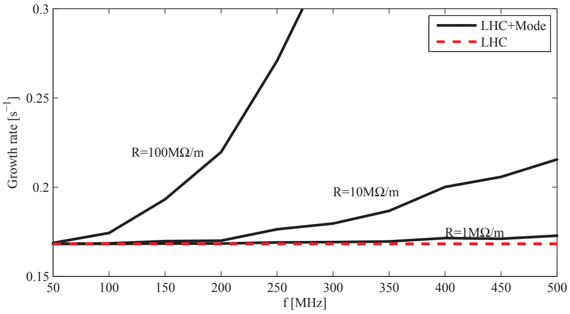

Figure 7: Most unstable mode growth rate adding over the 2016 LHC baseline impedance model (for β^* =40 cm in IP1 and IP5) one HOM with $Q = 20$, variable frequency f and shunt impedance R_s for $M = 2748$ nominal LHC bunches of $N_b = 1.2 \cdot 10^{11}$ ppb intensity and σ_z^{rms} =9 cm bunch length at $Q' = 5$ with transverse damper gain of 50 turns.

Concerning the TDI, a decreased performance was observed with beam in 2015 and successfully cross-checked with dedicated RF measurements. The higher impedance of TDI8 w.r.t. TDI2 has been correlated with a problem of the Ti coating on the hBN blocks which is presently being studied in detail by means of chemical analysis. The power loss for 2016 is expected to be a factor about 60 lower thanks to the Cu coating over the graphite bulk. This accounts only for resistive wall losses as the HOM-induced heating is unchanged. Attention should be also paid to the effect of grazing impacts, as this could volatilize the Cu coating increasing the heating on the device (but still a factor about 4 lower than the old TDIs). Dedicated machine measurements are foreseen to verify with beam the improved performance of the TDI in 2016 in view of the device upgrade for HL-LHC.

Concerning the TCTs, the HOM introduced with the device upgrade, has been mitigated by means of ferrite blocks. The undamped modes below 500MHz have been predicted not to be an issue for the LHC.

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