ELECTROMAGNETIC SIMULATIONS OF THE IMPEDANCE OF THE LHC INJECTION PROTECTION COLLIMATOR

B. Salvant, A. Grudiev, V. Baglin, B. Goddard, E. Métral, M. Timmins, CERN, Geneva

Abstract

During the Large Hadron Collider (LHC) 2011 run, significant vacuum and temperature increases were observed at the location of the LHC injection protection collimators (TDI) during the physics fills. Besides, measurements of the LHC transverse tune shift while changing the TDI gap showed that the impedance of the TDI was significantly higher than the LHC impedance model prediction based on multilayer infinite length theory. This contribution details the electromagnetic simulations performed with a full 3D model of the TDI to obtain both longitudinal and transverse impedances and their comparison with measured observables.

INTRODUCTION

The 450 GeV protons from SPS are injected into the LHC in IR2 and IR8. The beam to be injected passes through 5 horizontally deflecting septum magnets and 4 vertically deflecting kickers MKI. Uncontrolled beam loss resulting from errors in the MKI could result in serious damage of the equipments in the LHC injection regions, triplets or in the arcs. Therefore, a movable 2-sided absorber TDI has been installed about 70 m from the MKI (at a 90° phase advance) in order to protect the LHC equipments from damage. Each TDI consists of two 4.2 m absorber jaws: the upper jaw should intercept the injected beam which is not sufficiently deflected by the injection kickers and the lower jaw should intercept the affected circulating beam in the advent of a kicker mistiming [1].

During the 2011 run, pressure gauges near the TDI in points 2 and 8 recorded a significant beam induced pressure rise that appeared to affect the experiments, in particular the ALICE background in point 2 [2]. Following this observation, temperature probes were installed and a temperature increase was detected during the fill [3]. Increasing the parking gap of the TDI in physics from +/-20mm to +/-55mm – as it was initially foreseen – from fill 2219 damped the pressure increase, but not the temperature increase [3]. Decreasing the gap on the TDI in point 8 back to +/-20mm only for fill 2261 generated pressure rise again for TDI8 only, which confirmed the clear correlation of the pressure rise with the gap [4]. Increasing the TDI gap to the maximum available gap right after injection therefore seemed to be a solution to the vacuum problems and was implemented in the operational procedures right away.

Besides, beam measurements of the transverse tune shifts caused by TDI jaw movements gave hints that the TDI impedance was larger than predicted by the resistive wall and trapped modes model and may have degraded since the previous MD in May 2010 [4, 5]. This discrepancy in transverse impedance could be due to a problem with the coating integrity and/or thickness and it was therefore asked to check in-situ the status of the Titanium coating before the 2012 start-up.

Since the TDI is a crucial equipment for the protection of the LHC, it was decided to understand the origin of this pressure rise, and more detailed studies were performed: in particular analysis of abnormal beam losses and impedance studies, which could contribute to heating/outgassing of the TDI materials.

In complement to the previous studies of the resistive wall impedance of the composite TDI jaws [6], and of the trapped modes for the first design of the TDI [7], this contribution focuses on the simulation of the trapped modes of the current design of the TDI.

GEOMETRY AND 3D MODEL

Modelling and meshing the TDI design represents a real challenge due to the large size of the device (>5m) in conjunction with the presence of numerous small features in the vicinity of the beam (e.g. coating on the hexahedral boron nitride (hBN) jaw blocks, longitudinal gaps between the blocks, RF fingers, holes in the beam screen, thin RF shielding sheet), and the need to simulate a wide frequency range due to the short LHC bunch length in collision mode. Some assumptions have to be made in order to be able to run simulations with the current 3D codes (CST Particle Studio 2011 [8] and ANSYS HFSS v13 [9]). The 3D model was generated in CATIA and exported into HFSS and CST (see Fig. 1).

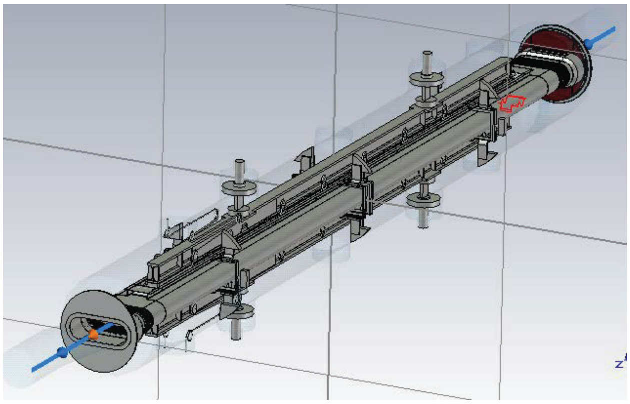

Figure 1: Simplified 3D model used for simulations (the vacuum tank is displayed as transparent to see the inside).

TIME DOMAIN SIMULATIONS

The CST Particle Studio 2011 wakefield solver was used to predict the wake fields and impedance generated by the interaction of a bunch with the TDI model in time domain (TD). The hexahedral mesh was the only available mesh that could be used with the wakefield solver at the time of these studies. Even with 60 million mesh cells (allowed by a 12-core 128 Gb Ram computer dedicated to these simulations), the code has trouble meshing precisely the geometry (see Fig. 2).

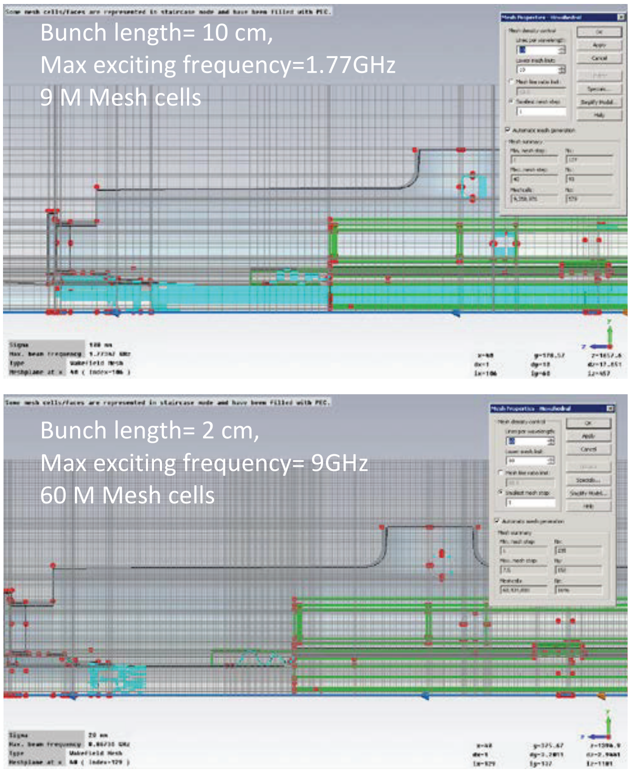

Figure 2: Zoomed side view of the mesh lines in the transition region between the beam pipe on the left and the jaw on the right. The exciting bunch length is decreased from 10 cm (top) to 2 cm (bottom), leading to a finer mesh. Problematic cells for the mesh are filled with perfect electric conductor (PEC), and displayed in light blue.

Despite the small thickness of the titanium coating on the hBN, the hBN blocks had to be modelled as bulk titanium. A Ferroxcube 4s60 ferrite model provided by the manufacturer was used for the damping ferrites at each end of the tank. A magnetic wall boundary condition is applied at the horizontal plane and perfect matching layer (PML or "open") boundary conditions are applied at the up/downstream ends.

The simulation results for the longitudinal impedance with jaw half gaps of 4 mm, 20 mm and 55 mm are displayed in Fig. 3. It can be seen that several sharp resonances between 1.2 and 1.5 GHz are predicted at low gaps (4 mm and 20 mm half gaps), which are strongly reduced when the nominal parking gap position is used (55 mm half gap). The signal increase above 1.8 GHz should be discarded, as caused mainly by noise enhanced by the finiteness of the simulated source bunch used for these simulations (8 cm). Smaller simulated bunch length should in fact be used with caution as very strong peaks above 2 GHz affect the precision of the Fourier-transformed wake potential at frequencies lower than 1 GHz, and generates significant negative real part of the longitudinal impedance. However, despite the 30 m simulated wake length, the wake potentials did not damp and therefore both the quality factor Q and the shunt impedance RT of the resonant modes are underestimated. In order to assess the power loss due to these longitudinal modes with a better accuracy, an eigenmode simulation campaign was launched.

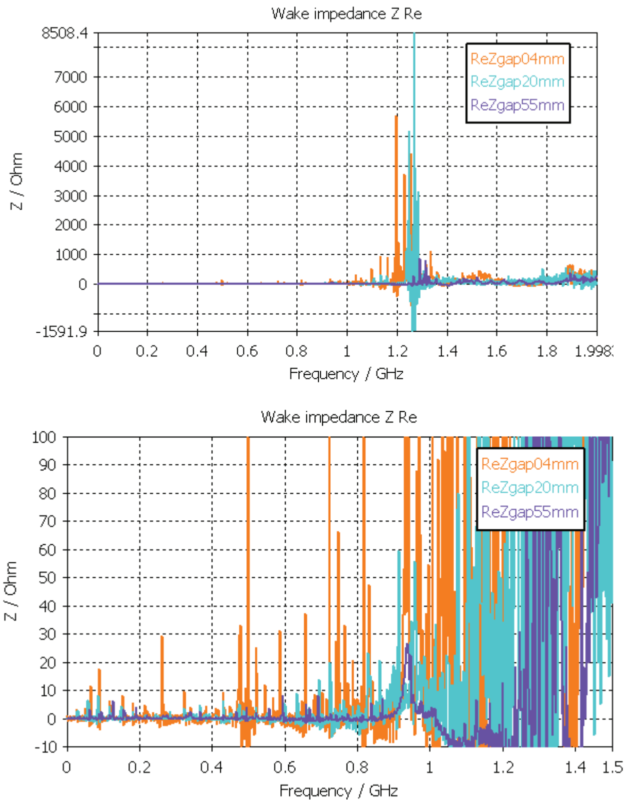

Figure 3: Real longitudinal impedance simulated by CST as a function of frequency for the TDI model with jaw half gaps of 4 mm (orange), 20 mm (cyan), 55 mm (purple) for a bunch length of 8 cm. The full view (top) only shows the main peaks around 1.2 GHz, while the zoomed view (bottom) enables to spot the low frequency peaks. The negative real part is attributed to precision issues of the Discrete Fourier Transform of the simulated wake potential.

FREQUENCY DOMAIN SIMULATIONS

After the frequencies of the most dangerous modes have been identified in TD simulations the frequency domain (FD) simulations of the modes parameters have been done using Ansys HFSS eigenmode solver [9].

First, all eigenmodes have been simulated from 10 MHz up to 1.4 GHz in order to check if all the modes are identified in TD simulations. The results of these simulations are shown in Fig 4. It shows a similar picture than the spectrum obtained in TD simulations: strongest modes at around 1.2 GHz with a forest of modes of shunt impedance of a few tens of Ohms down to low frequencies.

Second, more accurate simulations using first order basis functions have been perform in certain frequency ranges near the most dangerous modes in order to calculate their parameters more accurately. In particular the parameters related to the surface ohmic losses and to the surface fields were calculated more accurately. Two families of modes have been found: some at low frequency around 100 MHz and some at higher frequency around 1.2 GHz. Although the shunt impedance is very different by about a factor 100 the contribution to the RF heating is about the same due to the spectrum content of an LHC bunch [10]. Some examples of the surface field distribution of the two types of modes are presented in Fig. 5 in log-scale. Typically low frequency modes are spread along the whole device whereas the high frequency modes are localized near transition areas.

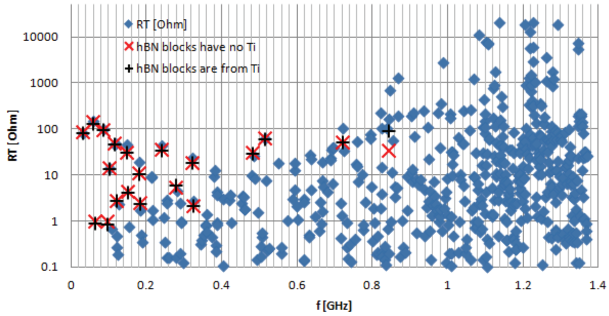

Figure 4: Shunt impedance of the TDI modes at half gap of 8 mm. Crosses are results of more accurate simulations with hBN blocks as hBN or titanium (without coating).

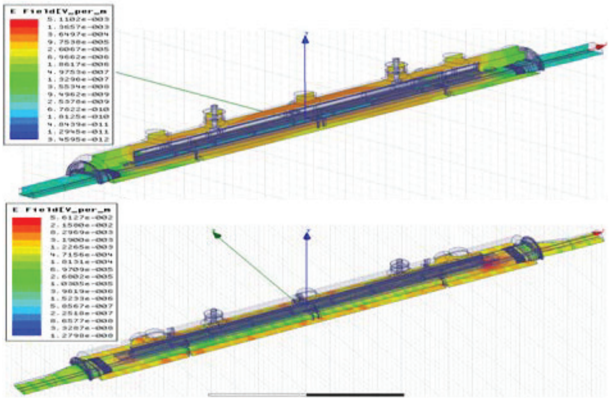

Figure 5: Typical surface electric field distribution of low (top) and high (bottom) frequency modes in TDI with the half gap of 8 mm are shown in log-scale.

ESTIMATE OF BEAM HEATING DUE TO THE TDI TRAPPED MODES

The following table gathers the parameters of the main modes found in FD simulations, along with the associated estimated power loss using the bunch spectrum measured in 2011 [11] and formula (11) described in Ref. [10] with a single beam intensity of 0.37 A. It is important to note that the estimation of the measured power spectrum is very coarse and represents a pessimistic value in case the mode frequency falls on 20 MHz beam spectrum line. In addition, two beams are circulating in the TDI at the same time and constructive or destructive interferences could occur. This effect is planned to be studied in a next step.

Table 1: Simulated parameters and estimated power loss for the main modes with one beam (half gap of 8 mm)

Freq. (GHz)	Q	RT (Ohm)	Pspectrum (dB)	Power loss (W)
0.03	164	80	0	11
0.06	193	131	0	18
0.09	205	92	0	13
0.12	239	47	-1	5.1
0.15	225	30	-1	3.3
0.51	460	60	-5	2.6
1.22	970	12830	-25	5.5
1.22	1001	5670	-25	2.5
1.23	815	2950	-25	1.2
1.23	873	6150	-25	2.7
1.26	582	3680	-25	1.6

As a consequence, accounting for all these assumptions, the power losses due to trapped modes could amount to 70 W.

SUMMARY

TD and FD simulations of the LHC TDI have been performed. Significant modes have been detected with both techniques at low and high frequencies. The total power loss for one mode is estimated to be as high as 20 W (at 60 MHz) and the total power loss for all modes amounts to around 70 W. Since this simulation campaign was launched, significant deformation of the beam screen has been observed on both TDIs [10]. Investigations were launched to assess if this deformation was due to RF heating or other sources. It was also decided to reinforce the design of the spare TDI, and come up with a new design for the restart in 2014 after the long shutdown.

REFERENCES

[1] B. Goddard, V. Kain, M. Lamont, *Function and operating conditions of the TDI beam absorber*, CERN EDMS document number 508735 (2004).
[2] G. Bregliozzi et al, *Vacuum observations*, CERN LHC Beam Operations Committee, 27/09/2011.
[3] V. Baglin et al, *TDI heating with large gaps*, CERN BE/ABP-ICE meeting, 26/10/2011.
[4] B. Salvant et al, *TDI impedance MD*, CERN 13th LHC Studies Working Group - 08/11/2011.
[5] N. Mounet, *Impedance effects on beam stability*, LHC Beam Operation Workshop, Evian 2011.
[6] E. Métral, *Resistive heat load for the TDI*, CERN LCE meeting, 11/06/2004.
[7] A. Grudiev, *First results on the simulation of trapped modes in TDI,* RLC meeting 22/04/2005.
[8] CST Computer Simulation Technology AG, www.cst.com.
[9] ANSYS HFSS, www.ansys.com.
[10] E. Métral, *Beam-induced heating/bunch length/RF and lessons for 2012*, LHC Performance Workshop, 2012.
[11] P. Baudrenghien, T. Mastoridis, *The LHC RF, 2011 and beyond*, LHC Beam Operation Workshop, Evian 2011.