CALCULATION OF WAKEFIELDS AND HIGHER ORDER MODES FOR THE VACUUM CHAMBER OF THE CMS, ATLAS, ALICE AND LHCb EXPERIMENTS FOR THE HL-LHC[†]

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Abstract

The High Luminosity Large Hadron Collider (HL-LHC) project was started with the goal to extend the discovery potential of the Large Hadron Collider (LHC). The HL-LHC study implies also upgraded dimensions of the experimental beam pipes of the CMS, ATLAS, ALICE and LHCb experiments. The trapped monopole and dipole Higher Order Modes (HOMs) and the short range wakefields for the new design of the vacuum chambers were calculated with help of the computer codes MAFIA and ECHO2D. The results of the short range wakefields calculations and the HOMs calculations are presented in this report. The short range wakefields are presented in terms of longitudinal and transverse wake potentials and also in terms of loss and kick parameters. Selected results from the HOMs calculations, including the frequency, the loss parameter, the R/Q and the Q value are presented.

INTRODUCTION

The High Luminosity LHC (HL-LHC) project was started in 2011 with the goal to extend the discovery potential of the LHC [1] by increasing the luminosity parameter by a factor 10 beyond its design value. The HL-LHC project implies also an upgraded configuration of the CMS, ATLAS, ALICE and LHCb detectors with new beam pipes. A summary of the results of the wake fields calculations and of the higher order modes calculations are presented in this report. The details of the studies can be found in several reports, see [2–5]. Two options with different sets of parameters are considered for the HL-LHC, see Tab. 1.

WAKEFIELDS AND HOMS

Wakefields

Numerical calculations with help of the codes ECHO2D [6, 7] or CST Studio Suite [8] give a possibility to obtain longitudinal monopole, longitudinal dipole and transverse dipole wake potentials. The wake potential [9] of a bunch with a charge q_1 is defined as:

$$\mathbf{W}(\mathbf{r}_{\perp 2}, \mathbf{r}_{\perp 1}, s) = \frac{1}{q_1} \int_0^L dz (\mathbf{E} + c\, \mathbf{e_z} \times \mathbf{B})_{t=(z+s)/c}. \quad (1)$$

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Table 1: Two Design Parameters Options for the HL-LHC

Parameter	Option 1	Option 2	
Energy	7	7	TeV
Ring circumference	26658.883	26658.883	m
Revolution frequency	11.245	11.245	kHz
RMS bunch length	7.5	7.5	cm
Number of bunches	2808	1404	
Number of particles per bunch	$2.2 \cdot 10^{11}$	$3.5 \cdot 10^{11}$	
Charge of one bunch	35.2	56.1	nC
Total beam current	1.11	0.89	A

In the case of cylindrically symmetric structure a multipole expansion can be used to describe the wake potential. The longitudinal and transverse components of the wake potential are connected by Panofsky-Wenzel theorem [10]. The transverse dipole wake potential can be obtained by integration of the transverse gradient of the longitudinal dipole wake potential:

$$W_\perp^{(1)}(s) = -\int_{-\infty}^{s} ds' W_{||}^{(0)}(s'). \quad (2)$$

Loss and Kick Parameters

The numerical calculations provide the monopole and dipole wake potentials $W_{||}^{(0)}(s)$ and $W_\perp^{(1)}(s)$. The total loss and total kick parameters can be obtained with help of the following formulas:

$$k_{||\mathrm{tot}}^{(0)} = \int ds\, W_{||}^{(0)}(s) g(s), \quad k_\perp^{(1)} = \int ds\, W_\perp^{(1)}(s) g(s), \quad (3)$$

where $g(s)$ is the normalized charge density of the bunch. The total kick parameter can be related to the transverse impedance (see [11])

$$(Z_\perp)_{eff} = 2\sqrt{\pi} \frac{\sigma_z}{c} k_\perp^{(1)}. \quad (8)$$

Higher Order Modes - HOMs

The electric and the magnetic fields of the higher order modes are calculated with the frequency domain solver of the computer code MAFIA [12–14]. The eigenvalue solver provides the frequency ($f = \omega/(2\pi)$) and the electric and the magnetic fields (E, B) for each higher order mode on a mesh. Further parameters as the stored energy U, voltage V, loss parameters $k_{||}(r)$, $k_\perp(r)/r^2$, R/Q, Q_{Cu}, Q_{Steel}, G_1, transverse impedance $Z_\perp$ and power loss parameters

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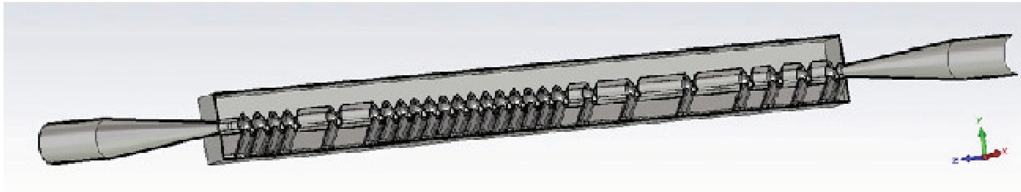

Figure 1: Model (3D) of the vacuum chamber of the LHCb vertex locator using CST studio suite [8].

P_{loss} were obtained as result of the post-processing [9]. The following relations are used in the post-processing for the frequency domain:

$$k_{||}(r) = \frac{| V(r) |^2}{4U}, \quad \frac{R}{Q} = \frac{2k_{||}(r)}{\omega}, \quad Q = \frac{\omega U}{P_{sur}}. \quad (4)$$

The Q-value is calculated from the field distribution on the wall of the vacuum chamber and surface resistivity. The dissipated power is calculated in the post-processor for a copper surface with resistivity $\sigma_{Cu} = 5.8 \cdot 10^7 (\Omega m)^{-1}$. The Q-value of any material can be obtained by scaling the value for copper $Q_{Mat} = Q_{Cu}\sqrt{\sigma_{Mat}/\sigma_{Cu}}$, where σ_{Mat} is the conductivity of material. The conductivity of steel σ_{St} is $1.5 \cdot 10^6 (\Omega m)^{-1}$ [15]. The loss parameter $k_{||}(r)$ is calculated on axis of the chamber ($r = 0$) for monopole modes and at an offset of $r = 1$cm from the axis for dipole modes. Therefore, R/Q parameters for monopole and for dipole modes are defined as:

$$\frac{R^{(0)}}{Q} = \frac{2k_{||}(r=0)}{\omega}, \quad \frac{R^{(1)}}{Q} = \frac{1}{r^2}\frac{2k_{||}(r)}{\omega}. \quad (5)$$

The transverse impedance is related to the $R^{(1)}/Q$:

$$Z_{\perp} = \frac{1}{\omega/c}\frac{R^{(1)}}{Q} Q \quad (6)$$

The units of $R^{(0)}/Q$ are Ohm. The units of $R^{(1)}/Q$ and $Z_{\perp}$ are Ohm/m^2 and Ohm/m respectively.

The power loss parameters P_{loss} can be obtained for each mode using the following relation:

$$P_{loss} = 2\frac{R}{Q} Q\, I^2 e^{-(\frac{2\pi f_{hom}}{c})^2 \sigma_z^2}, \quad (7)$$

where I is the total beam current (1.11 A or 0.89 A).

RESULTS

Short Range Wakefields

The details of the considered geometries of the vacuum chambers are presented in Ref. [2–5]. For the ATLAS, CMS and ALICE chamber a 2D-model of the structure was used, while the LHCb vacuum chamber is a complicated 3D structure, see Fig.1.

The results for the loss and kick parameters are summarized in Tab. 2. The mesh size is also included in the table. The longitudinal short range wakes for the ATLAS and LHCb chamber correspond to an almost purely inductive impedance. The loss parameter is very small for these

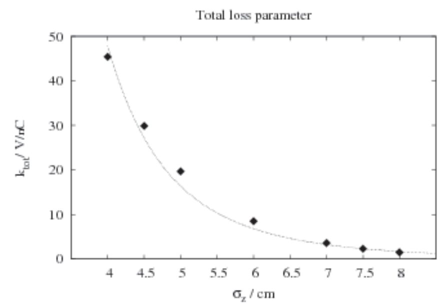

Figure 2: Total loss parameter versus rms bunch length for the CMS vacuum chamber.

chambers. The results for LHCb for the transverse plane are not included in Tab. 2 since the results depend on the used step size of the mesh [5]. The quoted result for the kick parameter of the ALICE chamber is based on a calculation without an artificial contribution from an step-out transition, see [4]. For the ATLAS and ALICE experiments

Table 2: Results for the Loss and Kick Parameters of the ATLAS, CMS, ALICE and LHCb Vacuum Chamber for a Gaussian Bunch with rms Bunch Length of $\sigma_z = 7.5$ cm

Parameter	Results	Δz/cm	Δr/cm
ATLAS			
$k^{(0)}_{\|\|tot}$ (V/nC)	$1.08 \cdot 10^{-6}$	0.2	0.1
$k^{(1)}_{\perp}$ (V/pCm)	1.72	0.2	0.1
CMS			
$k^{(0)}_{\|\|tot}$ (V/nC)	2.36	0.2	0.1
$k^{(1)}_{\perp}$ (V/pCm)	2.38	0.2	0.1
ALICE			
$k^{(0)}_{\|\|tot}$ (V/pC)	$1.83 \cdot 10^{-2}$	0.1	0.05
$k^{(1)}_{\perp}$ (V/pCm)	2.88	0.1	0.05
LHCb		Δx/cm	Δy/cm
$k^{(0)}_{\|\|tot}$ (V/pC)	$2.5 \cdot 10^{-5}$	0.5	0.5

also the kick parameters for additional bellows have been calculated [3, 4]. The kick parameter of one ALICE bellow is $k^{(1)}_{\perp} = 2.07$ V/pCm, while the corresponding parameter for the ATLAS bellow is $k^{(1)}_{\perp} \approx 1.9$ V/pCm.

It is worthwhile to note that the loss parameter strongly depends on the bunch length. The results for the CMS chamber are shown in Fig. 2.

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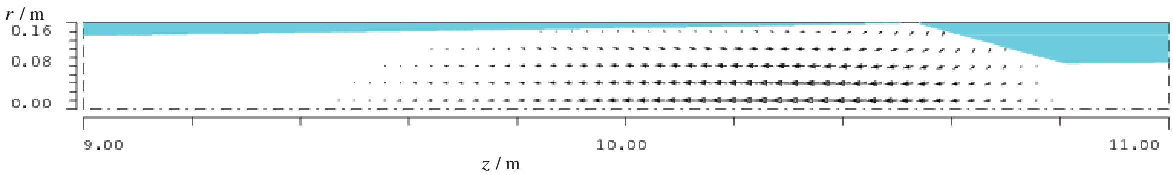

Figure 3: The electric field of monopole mode EE-1 in the CMS vacuum chamber (f = 751.0 MHz.

HOMs

The electric and magnetic fields of the higher order modes are calculated with the frequency domain solver of the computer code MAFIA [8, 12, 14]. A 2-dimensional model of the CMS vacuum chamber has been used since it is sufficient to model a cylindrically symmetric structure on a $r - z$-grid to obtain all important rf-parameters. There exist several trapped modes in the CMS vacuum chamber. The monopole mode with the lowest frequency of 751.0 MHz (EE-1) is trapped at the end of the End-cap-pipe about 10 m from the interaction point. The electric field of that mode is shown in Fig. 3. The loss parameter for all calculated modes are shown in Fig. 4. The data points are marked with circles for CMS chamber which is foreseen for the HL-LHC, while the crosses correspond to the present geometry, see Ref. [16].

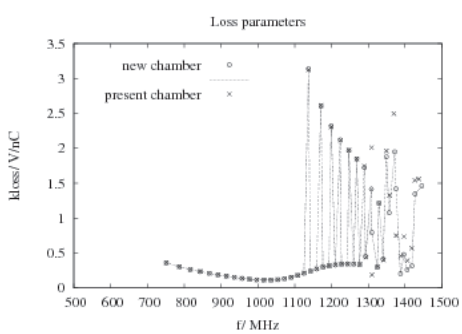

Figure 4: Loss parameters of the monopole modes versus frequency for the CMS chamber.

CONCLUSION

The wakefields and higher order modes of the new beam pipe of the ATLAS, CMS, ALICE and LHCb detectors for the High Luminosity LHC configuration (HL-LHC) have been calculated. The results indicate that the impedance of the chambers for the HL-LHC of the ATLAS, CMS, ALICE experiments is not significantly larger compared to the presently installed chambers, provided that the rms bunch length is σ_z = 7.5 cm. For the LHCb chamber further investigations seem to be necessary.

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