EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ATS-2009-118

WAKE AND HIGHER ORDER MODE COMPUTATIONS FOR THE CMS EXPERIMENTAL CHAMBER AT THE LHC

R. Wanzenberg, DESY, Hamburg, Germany, and E. Métral, CERN, Genève, Switzerland

Abstract

Wakefields and trapped Higher Order Modes (HOMs) in the CMS experimental chamber at the LHC are investigated using a geometrical model which closely reflects the presently installed vacuum chamber. The basic rf-parameters of the HOMs including the frequency, loss parameter, and the Q-value are provided. To cover also transient effects the short range wakefields and the total loss parameter has been calculated, too. Most numerical calculations are performed with the computer code MAFIA. The calculations of the Modes are complemented with an analysis of the multi-bunch instabilities due to the longitudinal and dipole modes in the CMS vacuum chamber.

Presented at the Particle Accelerator Conference (PAC09)
May 4-8 2009, Vancouver, Canada

Geneva, Switzerland,
31 July 2009

WAKE AND HIGHER ORDER MODE COMPUTATIONS FOR THE CMS EXPERIMENTAL CHAMBER AT THE LHC

R. Wanzenberg#, DESY, Hamburg, Germany, and E. Métral, CERN, Genève, Switzerland

Abstract

Wakefields and trapped Higher Order Modes (HOMs) in the CMS experimental chamber at the LHC are investigated using a geometrical model which closely reflects the presently installed vacuum chamber. The basic rf-parameters of the HOMs including the frequency, loss parameter, and the Q-value are provided. To cover also transient effects the short range wakefields and the total loss parameter has been calculated, too. Most numerical calculations are performed with the computer code MAFIA. The calculations of the Modes are complemented with an analysis of the multi-bunch instabilities due to the longitudinal and dipole modes in the CMS vacuum chamber.

INTRODUCTION

LHC

The Large Hadron Collider (LHC) is intended to provided proton-proton collisions with a center-of-mass energy of up to 14 TeV and a luminosity of $1.0 \cdot 10^{34}$ cm^{-2} s^{-1}. The main parameters of the accelerator for luminosity operation are shown in Table 1, and a more detailed list can be found in Ref. [1]. The LHC has an 8-fold symmetry with eight arc sections and eight straight sections which contain experiments and systems for the machine operation. The two counter circulating proton beams will collide at the interaction points (IPs) in sector 1 and 5, where the experiments ATLAS (IP 1) and CMS (IP 5) have been installed.

Table 1: Main parameters of the LHC [1].

Parameter	Symbol	Value	Unit
Proton Energy	E_p	7000	GeV
Circumference	C	26658.95	m
Number of bunches	N_b	2808	
Single bunch charge	q_b	18.4	nC
Bunch length	σ_z	7.5	cm
Tune	ν_x/ν_y	64.31/59.32	
Harmonic number	h	35640	
Momentum comp.	α_p	3.225	10^{-4}
Total RF voltage	V_{rf}	16	MV

CMS Vacuum chamber

Inside of the CMS (Compact Muon Solenoid) experiment a vacuum chamber is installed which is accommodated to the needs of the installed detector components. A 3D-view of the vacuum system is shown in Fig. 1 and a simplified model of the vacuum chamber is shown in Fig. 2 which has been used for the calculations of the wakefields and the HOMs [2].

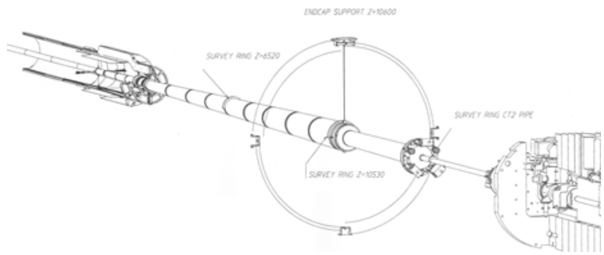

Figure 1: A 3D view of the CMS vacuum chamber. The beam pipe is shown from the interaction point to the compensation module.

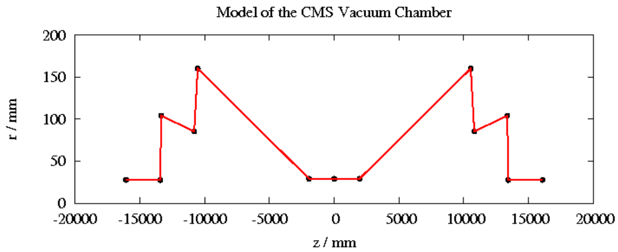

Figure 2: A simplified model of the CMS vacuum chamber. The chamber is symmetric with respect to the interaction point (z = 0 m).

Wake fields and HOMs

A beam circulating in a storage ring interacts with its vacuum chamber surroundings via electromagnetic fields. These wake fields in turn act back on the beam and can lead to instabilities, which limit either the achievable current per bunch or the total current or even both. The wake potential of a Gaussian with total charge q is defined as:

$$\vec{W}(s) = \tfrac{1}{q}\int dz\, (\vec{E} + \vec{v} \times \vec{B})_{t=(s+z)/c}. \qquad (1)$$

The total loss parameter $k_{\|}$ and the kick parameter $k_{\perp}$ are defined as:

$$k_{\|tot} = \int ds\, W_{\|}(s)\, g(s), \quad k_{\perp} = \int ds\, W_{\perp}(s)\, g(s), \quad (2)$$

where $W_{\|}(s)$ is the longitudinal and $W_{\perp}(s)$ is the transverse wake potential of a Gaussian bunch with normalized bunch charge density g(s). The contribution of HOMs to the wake potential is the convolution of the Gaussian charge distribution with the wake potential:

#rainer.wanzenberg@desy.de

$$W_{\|HOM}(s) = -\sum_n k_{\|n} \cos(2\pi f_n s/c)\exp(\frac{2\pi f_n}{2Q_n} s/c), \quad (3)$$

where f_n is the frequency, $k_{\|n}$ the loss parameter and Q_n the Q-value of the mode n. The energy loss of a point charge q to the electromagnetic field of the mode n is: $\Delta E = q^2 \left|k_{\|}\right|$.A detailed introduction to the definition of rf-parameters of HOMs is given in Ref. [3].

HIGHER ORDER MODES

For the calculations of the HOMs we have used the eigenvalue solver module of the MAFIA code [4, 5]. The right half of the model of the CMS vacuum chamber which is shown in Fig. 2 has be used to obtain the electric and magnetic fields of the HOMs on an r-z grid with a step size of 1 mm (about 1.3 million mesh points).

The loss parameters and the Q-values of the monopole modes are shown in Fig. 3 and Fig. 4 versus the frequencies of the modes. The loss parameters of dipole modes integrated at a radial offset of r = 1 cm are shown in Fig. 5.

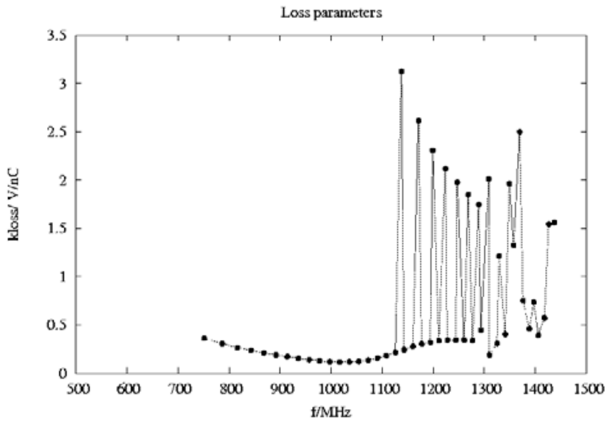

Figure 3: Plot of the loss parameters of the monopole modes versus frequency. (The dotted line is intended only to guide the eye.)

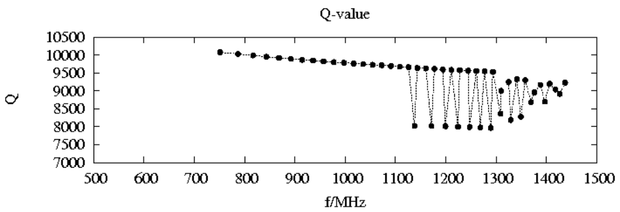

Figure 4: Plot of the Q-values of the monopole modes versus frequency for stainless steel.

The beam pipe close to the interaction point (IP) is made from Beryllium (Be) while the other parts of the vacuum chamber are made from stainless steal. The vacuum chamber is coated with NEG (Non Evaporable Getter) material which is covered in some regions with a thin (0.1μm thick) copper layer. Since the thickness of the NEG layer and the copper coating is much thinner than the skin depth at a typical mode frequency of 1 GHz the Q-value will be dominated by the material of the vacuum chamber which is stainless steel in all regions were HOMs are trapped inside the CMS vacuum chamber.

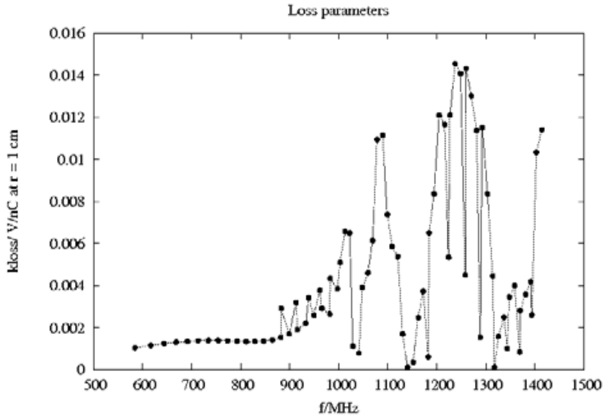

Figure 5: Plot of the loss parameters of the dipole modes versus frequency.

If a mode is resonantly excited the power loss in that mode will be:

$$P_{res,n} = \frac{k_{\|,n}}{2\pi f_n} Q_n \left|\tilde{g}(2\pi f_n)\right| I_{tot}^{2}, \quad (5)$$

where $\tilde{g}$ is the Fourier transform of the Gaussian charge distribution g(s). Using the loss parameters and Q-values of all modes (Fig. 3 and 4) and the total beam current of I_{tot} = 0.582A the resonant power is plotted for each mode in Fig. 6. In the worst case the beam can put a power of up-to 65 W into one mode.

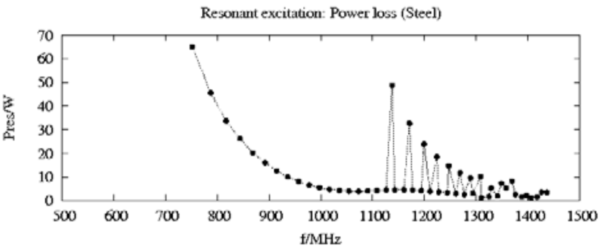

Figure 6: Resonant power loss versus the mode frequency.

WAKE COMPUTATIONS

Since the CMS vacuum chamber is rotationally symmetric with respect to the longitudinal axis it is convenient to use a two dimensional (r, z) computer code for numerical wakefield calculations. The ECHO2D code [6,7] was used to calculate the Monopole and Dipole wakefield of the CMS vacuum chamber (see Fig. 7). The total loss parameter is $k_{\|tot}$ = 2.36 V/nC and the total kick parameter is $k_{\perp}$ = 2.36 V/(pC m).

MULTI-BUNCH INSTABILITIES

The transverse trapped modes of the CMS vacuum chamber can lead to transverse coupled-bunch instability in the LHC. The first 75 modes have been identified and are given in Fig. 4. The modes should be stabilised by

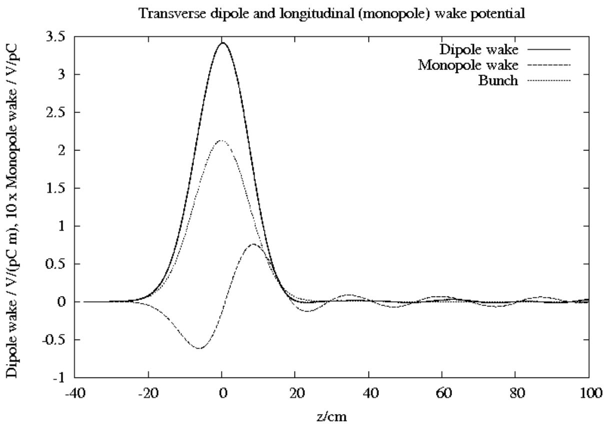

Figure 7: Longitudinal and transverse wake potential of the CMS vacuum chamber for a bunch length of $\sigma_z = 75$ mm. (Note the different units and scale).

Landau damping if for one reason or another the transverse feedback cannot be used at top energy. In this case, the (minus) imaginary part of the tune shift (for the entire machine!) should not exceed ~ 1.5 10^{-4} [8]. Assuming a transverse betatron function of ~ 200 m (as most of the critical modes are located at ~ 10 m from the IP), the (minus) imaginary part of the tune shift at 7 TeV for mode with highest shunt impedance (11.9 kΩ/m for mode 53) and assuming that a betatron line falls exactly on the resonance is ~ 3 10^{-9}, corresponding to an instability rise-time of ~ 5000 s. This value seems consistent with values quoted in Ref. [9] where a slightly different geometry was considered. The (minus) imaginary part of the tune shift can be deduced from Fig. 8, taking the maximum value of the instability growth rate (~ 2 10^{-4}) and dividing it by the revolution (angular) frequency.

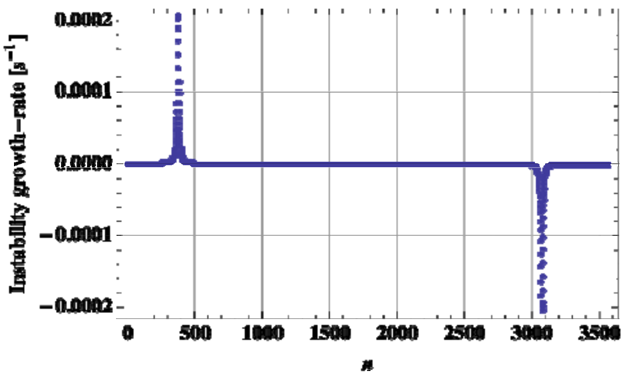

Figure 8: Instability growth rate vs. the transverse coupled-bunch mode number for the case of the mode 53 (only), assuming a Gaussian bunch and considering the most critical single-bunch mode number 3 (see Fig. 9).

Taking into account all the modes (see Fig. 9. where the impedance has been weighted by the transverse betatron function), the values change slightly to ~ 4 10^{-9}, corresponding to an instability rise-time of ~ 3500 s. At injection, the betatron function will be different and the rise-time of the instability should be smaller by a factor of ~ 16 (i.e. 7 TeV / 450 GeV). However, in all cases the transverse coupled-bunch instability rise-times are large enough that the instability can be damped by the transverse feedback system or through Landau damping.

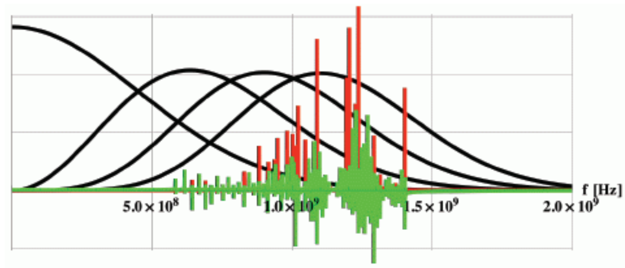

Figure 9: Transverse impedance (weighted by a betatron function of 200 m, corresponding to the value at ~ 10 m from the IP) for all the modes: real part in red, imaginary part in green, and (Gaussian) bunch spectrum in black for the first 4 single-bunch modes.

CONCLUSION

The trapped Higher Order Modes and the Wake potentials of a Gaussian bunch in the vacuum chamber of the CMS experiment at the LHC have been calculated using a geometrical model which closely reflects the presently (in 2008) installed vacuum chamber. The transverse coupled-bunch instability rise-times are large enough that the instability can be damped by the transverse feedback system or through Landau damping.

REFERENCES

[1] "LHC Design Report - Vol 1 the LHC Main Ring", CERN-2004-003-V-1, 2004.

[2] W. Zeuner, "CMS vacuum system", private communication (2008).

[3] R. Wanzenberg, "Calculation of Higher Order Modes and Wakefields for the Vacuum Chamber of the CMS Experiment at the LHC", CERN, LHC Project Note 418, 2009.

[4] MAFIA Version 4.200, CST AG, Bad Nauheimer Str. 19, D-64289 Darmstadt (2002).

[5] T. Weiland, "On the Numerical Solution of Maxwell's Equations and Applications in the Field of Accelerator Physics", Part. Acc. 15 (1984).

[6] I. Zagorodnov and T. Weiland, "TE/TM field solver for particle beam simulations without numerical Cherenkov radiation", Phys. Rev. ST Accel. Beams 8 (2005) 042001.

[7] I. Zagorodnov, "Indirect methods for wake potential integration", Phys. Rev. ST Accel. Beams 9 (2006) 102002 [arXiv:physics/0606049].

[8] E. Métral et al., Transverse Impedance of LHC Collimators, Proc. PAC2007, Albuquerque, New Mexico, USA, June 25-29, 2007.

[9] O. Bruning, "Longitudinal and transverse Modes in the CMS Experimental Chamber", CERN, LHC Project Note 36, March 1996.