5-2017

Wakefield Analysis of Superconducting RF-Dipole Cavities

Subashini De Silva
Old Dominion University

Jean Delayen
Old Dominion University

Repository Citation

De Silva, Subashini and Delayen, Jean, "Wakefield Analysis of Superconducting RF-Dipole Cavities" (2017). *Physics Faculty Publications*. 322.
https://digitalcommons.odu.edu/physics_fac_pubs/322

Original Publication Citation

De Silva, S., & Delayen, J. (2017). *Wakefield Analysis of Superconducting RF-Dipole Cavities.* Paper presented at the 28th Linear Accelerator Conference, 25-30 September 2016, East Lansing, MI.
https://doi.org/10.18429/JACoW-LINAC2016-MOPLR031

WAKEFIELD ANALYSIS OF SUPERCONDUCTING RF-DIPOLE CAVITIES*

S. U. De Silva[1,2#], J. R. Delayen[1,2],
[1]Center for Accelerator Science, Old Dominion University, Norfolk, VA 23529, USA.
[2]Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

RF-dipole crabbing cavities are being considered for a variety of crabbing applications. Some of the applications are the crabbing cavity systems for LHC High Luminosity Upgrade and the proposed Electron-Ion Collider for Jefferson Lab. The design requirements in the current applications require the cavities to incorporate complex damping schemes to suppress the higher order modes that may be excited by the high intensity proton or electron beams traversing through the cavities. The number of cavities required to achieve the desired high transverse voltage, and the complexity in the cavity geometries also contributes to the wakefields generated by beams. This paper characterizes the wakefield analysis for single cell and multi-cell rf-dipole cavities.

INTRODUCTION

In rf cavities electromagnetic fields are excited by the charged particle beam traversing through the cavity, which then may affect the dynamics of the beam itself. A bunch on-axis can generate longitudinal wakes and a bunch at an offset may generate transverse wakefields [1]. Longitudinal wakefields can cause power losses in the cavity and increase in energy spread in the beam. Similarly transverse effects can amplify the effects leading to beam instabilities.

The wakefield effects can be characterised into wake potentials and wake impedances. These excited wakefields then can be related to the higher order modes (HOMs) present in the cavity.

Wake potential is defined as the change of momentum in a charge particle following a bunch with charge Q_b at a distance s. The longitudinal wake potential is calculated by integrating the longitudinal electric fields as

$$\overrightarrow{W_z}(x,y,s)=\frac{1}{Q_b}\int_{-\infty}^{\infty}\overrightarrow{E_z}\left(x,y,z,t=\frac{s+z}{v}\right)\mathrm{d}z, \qquad (1)$$

and the transverse wake potential is given by

$$\overrightarrow{W_t}(x,y,s)=\frac{1}{Q_b}\int_{-\infty}^{\infty}\left[\begin{array}{l}\vec{E}\left(x,y,z,t=\dfrac{s+z}{v}\right)\\ \qquad +\vec{v}\times\vec{B}\left(x,y,z,t=\dfrac{s+z}{v}\right)\end{array}\right]\mathrm{d}z. \qquad (2)$$

The transverse wakefield is calculated with the integrated the wake potential at an offset from the beam axis and using the Panofsky-Wenzel theorem [2] as shown in Eq. (3).

$$\overrightarrow{W_t}(x,y,s)=-\nabla_t\int_{-\infty}^{s}W_z(x,y,s')\,\mathrm{d}s' \qquad (3)$$

Wakefield impedance in frequency domain is derived by applying the Fourier transformation on wake potentials.

$$Z(\omega)=\int_{-\infty}^{\infty}W(t)\exp(-i\omega t)\,\mathrm{d}t \qquad (4)$$

The wake potentials are generated for a Gaussian form of bunch charge distribution ($Q(s)$) given in Eq. (5) with bunch length (σ_z) and charge per bunch (Q_b).

$$Q(s)=Q_b\lambda(s)=\frac{Q_b}{\sqrt{2\pi}\sigma_z}\exp\left(-\frac{s^2}{2\sigma_z^2}\right) \qquad (5)$$

The frequency spectrum of the Gaussian charge distribution is specified as

$$F(\omega)\sim\exp\left(-\frac{\omega^2\sigma^2}{2c^2}\right) \qquad (6)$$

gives the frequency range of which wake potentials are evaluated. The loss factor for the longitudinal wakes are determined by

$$k_z=-\int_{-\infty}^{\infty}W_z(s)\lambda(s)\,\mathrm{d}s\,. \qquad (7)$$

Similarly the kick factor for transverse wakefields are defined as

$$k_t=\frac{1}{r_0}\int_{-\infty}^{\infty}W_t(s)\lambda(s)\,\mathrm{d}s \qquad (8)$$

where r_0 is the offset from beam axis at which wake potentials are evaluated.

This paper presents the wakefields analysis for the two rf-dipole crabbing cavities of 400 MHz for LHC High Luminosity Upgrade and 952.6 MHz cavity for Jefferson Lab Electron-Ion Collider.

400 MHz CRABBING CAVITY

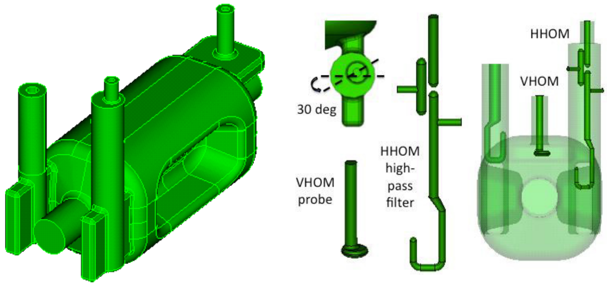

Figure 1: 400 MHz rf-dipole crabbing cavity.

The 400 MHz rf-dipole crabbing cavity shown in Fig. 1 is one of the two crabbing cavities designed for LHC High Luminosity Upgrade [3]. The crabbing cavity is expected

---

*Work supported by DOE via US LARP Program and by the High Luminosity LHC Project. Work was also supported by DOE Contract No. DE-AC02-76SF00515.
#sdesilva@jlab.org

to deliver a transverse momentum in the horizontal to crab the beam at the interaction point for CMS experiment in LHC. The crabbing cavity has two HOM couplers: a horizontal HOM (HHOM) coupler and a vertical HOM (VHOM) coupler [4]. The HHOM coupler is a high pass filter that damps the horizontal dipole modes and some of the accelerating modes. The VHOM coupler supresses the vertical dipole modes and some accelerating modes that are not damped by the HHOM coupler. The coupling strength with the corresponding impedance for the crabbing cavity is shown in Fig. 2.

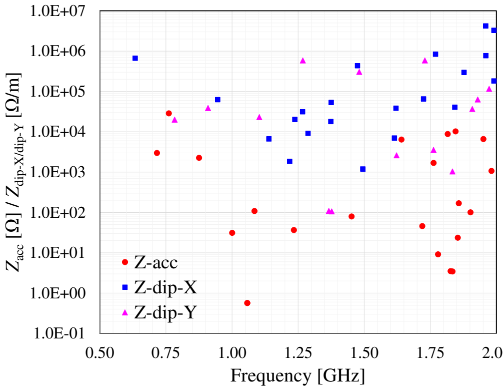

Figure 2: Longitudinal (Z_{acc}) and transverse impedances ($Z_{dip\text{-}X/dip\text{-}Y}$) of the 400 MHz crabbing cavity.

The LHC beam parameters of the proton beams for the luminosity upgrade are listed in Table 1 [5].

Table 1: HL-LHC beam parameters

Parameter	Value	Units
Beam energy	7	TeV
Beam current	1.02	A
Bunch spacing	25	ns
rms bunch length (σ_z)	7.55	cm

The proton beam in LHC doesn't follow a precise Gaussian form. Therefore, a beam with a σ_z of 5 cm was considered to evaluate the HOM excitation beyond 2 GHz. The bunch charge distribution is shown in Fig. 3. The wakefields were calculated using CST Wakefield Solver.

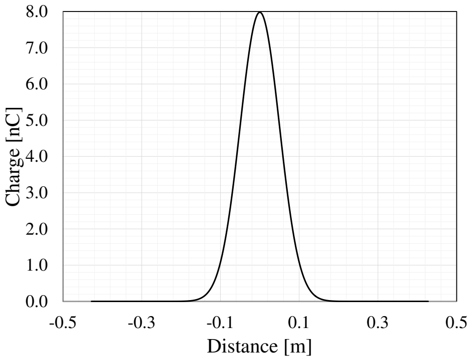

Figure 3: Charge distribution.

Longitudinal and transverse wake potentials were obtained for a single bunch of 1 nC charge for wakefields with lengths of 100 m and 500 m. The transverse wake potentials are calculated by simulating two parallel beams of opposite charge passing through the cavity with an offset of 5 mm from the beam axis. The normalized longitudinal wake potential and wake impedance are shown in Fig. 4. The wake fields decay completely for a single bunch beam excitation.

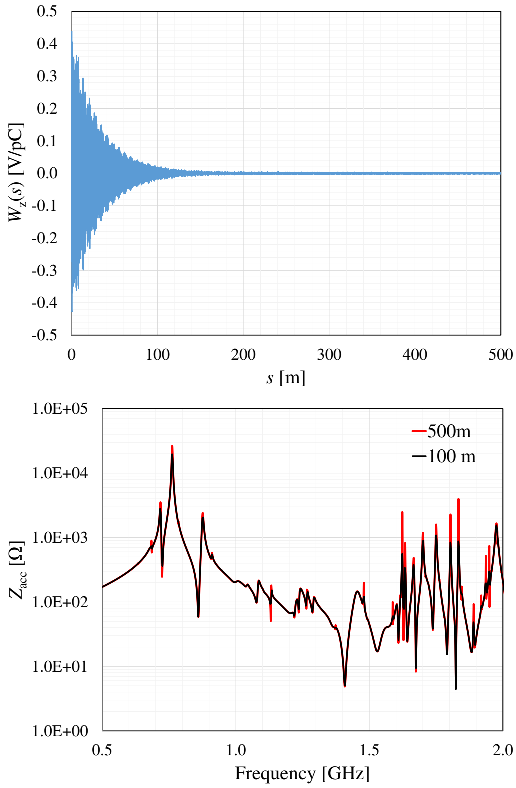

Figure 4: Longitudinal wake potential (top) and wake impedance (bottom).

The amplitude of the wake impedance of the excited HOMs are effectively resolved at wakefields with longer length. The estimated loss factor (k_{cc}) is 0.176 V/pC where the power loss due to the excited monopole modes is 4.5 kW. The transverse wake impedance in both horizontal and vertical directions are shown in Figs. 5 and 6. The corresponding kick factors are k_x = 0.41 V/pC/m and k_y = 0.06 V/pC/m.

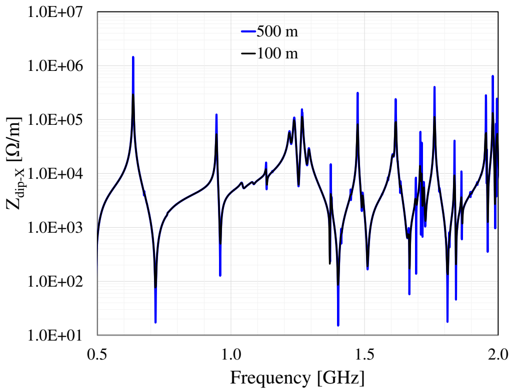

Figure 5: Transverse wake impedance in horizontal direction.

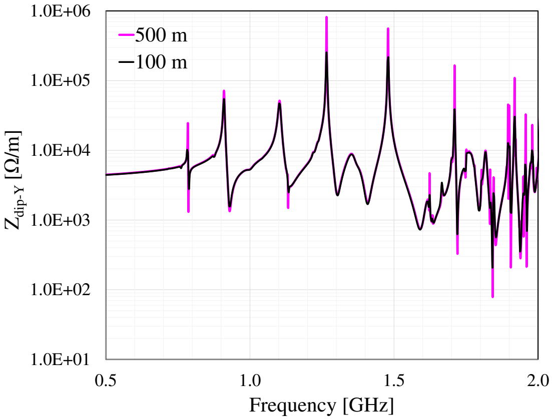

Figure 6: Transverse wake impedance in vertical direction.

952.6 MHz CRABBING CAVITY

A 952.6 MHz multi-cell rf-dipole as shown in Fig. 7 is considered as the crabbing cavity for the proposed Jefferson Lab electron-ion collider in crabbing both electron and proton beams [6]. The design with varying beam aperture is investigated to study the effects due to wakefield excitation.

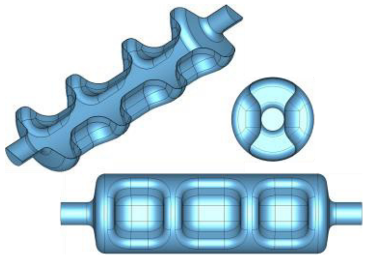

Figure 7: 952.6 MHz multi-cell rf-dipole cavity.

A single bunch with a Gaussian charge distribution and σ_z = 3 cm was used to analyse the wakefield effects on the multi-cell cavity with beam apertures of 50 mm, 60 mm, and 70 mm for a wake length of 300 m. The preliminary analysis for the bare cavities shows similar HOM excitation as shown in Fig. 8. The smaller beam aperture has wider HOM separation and large beam aperture has low cut-off frequency that makes extraction of HOMs easier.

CONCLUSION

The wakefield analysis for the crabbing cavities was carried out for short range wakefields with single bunch. The 400 MHz crabbing cavity requires the study of multi-bunch long range wake field analysis to fully resolve the accelerating and dipole HOMs. The loss factor estimates the HOM power loss in kW range due to the monopole modes. The cavity asymmetry contributes to the different kick factor in transverse impedance.

The 952.6 MHz crabbing cavity was studied to determine the dependence due to beam aperture on the effect on wakefield excitation. Further study including HOM couplers is required to accurately estimate losses due to HOMs.

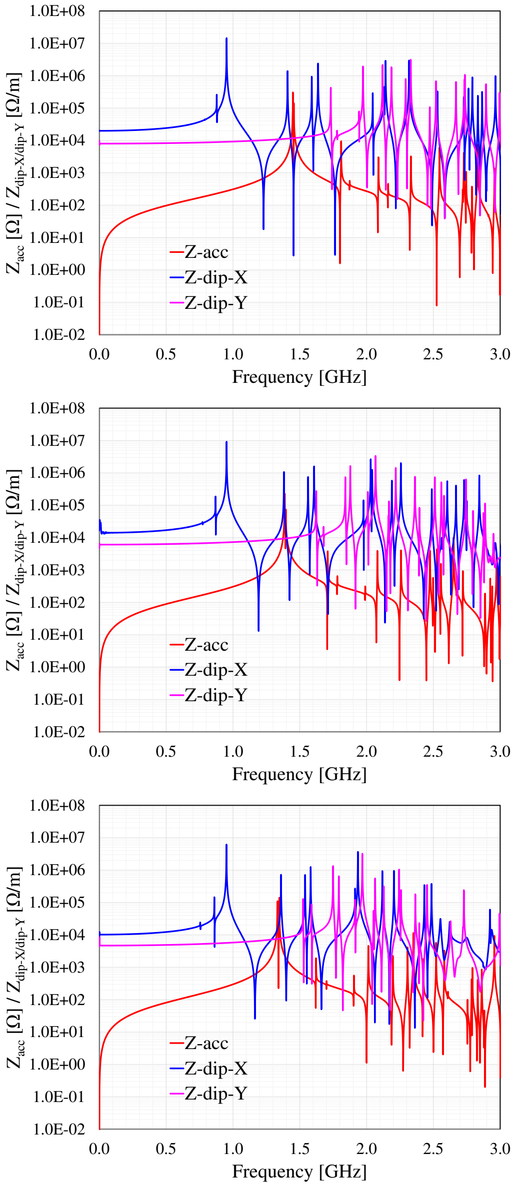

Figure 8: Longitudinal and transverse wake impedances for multi-cell rf-dipole cavities with beam apertures of 50 mm (top), 60 mm (middle), and 70 mm (bottom).

REFERENCES

[1] T. Weiland and R. Wanzenberg, “*Wake Fields and Impedances*”, CCAS-CAT-CERN Accelerator School, Indore (1993), p. 140.

[2] W. K. H. Panofsky and W. A. Wenzel, Rev. Sci. Instrum. **27**, 967 (1956).

[3] S. U. De Silva, and *et. al.*, in *Proc.* of SRF 2015, Whistler, BC, Canada (2015), p. 1222.

[4] Z. Li, and *et. al.*, in *Proc.* of IPAC 2015, Richmond, VA, USA (2015), p. 3492.

[5] G. Apollinari, and *et. al.*, “HL-LHC Preliminary Design Report”, CERN-2015-005, Geneva (2015).

[6] S. U. De Silva, and *et. al.*, in *Proc.* of IPAC 2016, Busan, Korea (2016), p. 2469.