WAKEFIELD LOSS ANALYSIS OF THE ELLIPTICAL 3.9 GHZ THIRD HARMONIC CAVITY*

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Abstract

Third harmonic 3.9 GHz elliptical cavities are planned to be used in many particle accelerator projects such as XFEL, NGLS, and ASTA. In this paper, the wakefield losses due to bunches from 8 mm down to ultra short bunches of 10 μm are analysed. Both the loss and kick factors are numerically calculated for bunches of relatively long length (>1 mm) using CST wakefield solver. The data is then used to asymptotically extrapolate the values for ultra-short bunches by finding the wake functions. These calculations are essential to estimate the cryogenic losses in cryomodules and for beam dynamic analysis.

INTRODUCTION

Third harmonic cavities are commonly used in the particle accelerators of light sources to improve the bunch stability and compensate for the distortion that could happen between the sinusoidal accelerating field and the relatively long beam bunches [1-6].

Third harmonic 3.9 GHz cavities are currently under production for several projects. For instance, DESY's XFEL and FNAL's ASTA. Other future light sources (like NGLS) are also planning to use the third harmonic cavities.

In collaboration with DESY, Fermilab constructed a third harmonic cryomodule for the Free electron LASer in Hamburg (FLASH) facility [1-4]. Each cryomodule contains four superconducting radio frequency (SRF) cavities operating at 3.9 GHz. The third harmonic 9-cell cavities are designed to operate at 2 K in the TM_{010} π-mode at an accelerating gradient of 14 MV/m, summing up to a total energy gain of 20 MeV per cryomodule. These cavities operate in a decelerating phase of 179º relative to the beam phase, and are optimized for 9 mA of beam current.

In addition, another cryomodule will be fabricated for Fermilab Advanced Superconducting Test Accelerator (ASTA). ASTA plans to deliver 50 MeV beam for a broad range of beam-based experiments to push limits of particle-beam generation, acceleration and manipulation. ASTA plans to employ Superconducting 3.9 GHz cavities for bunch linearization.

Before accelerating beam with third harmonic cavities, it is imperative to estimate the cryogneic losses by analysing the wakefield losses. This paper reports on an extensive wakefield analysis, carried out on these third harmonic cavities, including the simulated loss and kick factors for sub cm beam bunches. Based on the simulated data and using an asymptotic approximation, we estimate the loss and kick factors for sub mm beam bunches.

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WAKEFIELD SIMULATION FOR SUB CM BEAM BUNCHES

Figure 1 shows the geometry of the third harmonic 3.9 GHz 9-cells elliptical cavity. In different to the wakefield analysis in [5], we resorted to CST microwave studio to compute the wakefields inside a single cavity due to relatively long bunches, where the structure is excited by a longitudinal line current [7]. The line current is placed on the beam axis for the loss factor calculations, while the line is displaced off axis for the kick factor calculations. In both cases, the line current representing the beam is formed with a longitudinal, Gaussian shaped charge distribution.

Accuracy of the analysis was checked versus the mesh size. Typically, the ratio between the bunch sigma (standard deviation of the Gaussian distribution) to the mesh step size in the longitudinal direction *Sigma/h* is used to check the accuracy of the analysis with conventionally using *Sigma/h* of 20 as a satisfactory level of mesh refinement. In this analysis, we have used a *Sigma/h* of 30, as shown in Fig. 2. Mesh size of approximately 70 million elements (per quarter of cavity) was needed for the relatively short RMS bunch length of 2 mm, as shown in Fig. 2.

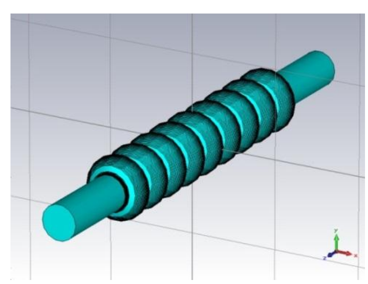

Figure 1: Geometry of the third harmonic 3.9 GHz cavity.

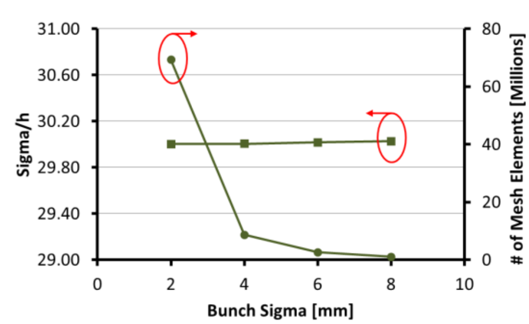

Figure 2: Sigma/h and number of mesh elements vs. bunch sigma.

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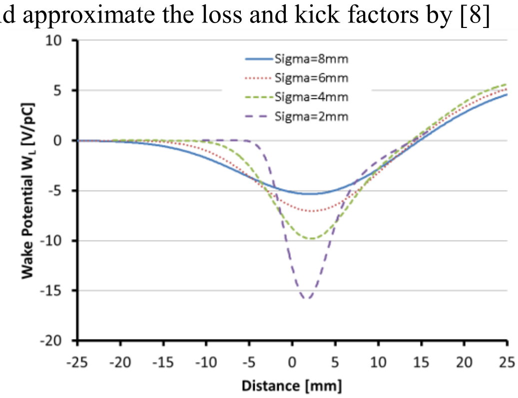
Figure 3 shows the wake potential both in longitudinal and transverse directions for various RMS bunch lengths ranging from 8 mm to 2 mm. As expected, the peak absolute value of the wake potential increases as the RMS bunch length decreases. The longitudinal wake potential increases from 5 V/pC to 16 V/pC as the RMS bunch length decreases from 8 mm to 2 mm. On the other hand, the transverse wake potential increases from 0.4 V/pC/mm to 0.6 V/pC/mm as the RMS bunch length decreases from 8 mm to 2 mm. The peak of the longitudinal wake potential happens at approximately 2 mm distance for all bunch RMS lengths, while the peak transverse wake potential happens at approximately12 mm distance.

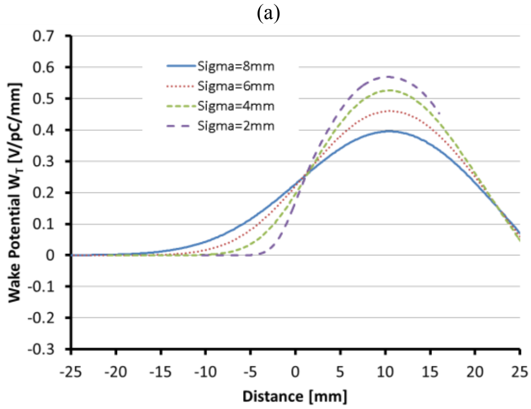
The loss and kick factors are shown in Fig. 4 (a) and (b), respectively. The loss factor varies from 3.5 V/pC to 10.5 V/pC as the RMS bunch length decreases from 8 mm to 2 mm, as shown in Fig. 4(a). On the other hand, the kick factor decreases from 0.22 V/pC/mm to 0.17 V/pC/mm over the same range.

ASYMPOTITIC APPROXIMATION FOR SUB MM BEAM BUNCHES

Computing the wakefield losses for ultra-short bunches is not possible using CST because of the mesh size limitation (for sub mm bunches, the mesh size would be in microns). In such case of ultra-short bunches, asymptotic approximation is typically used, where we could approximate the loss and kick factors by [8]

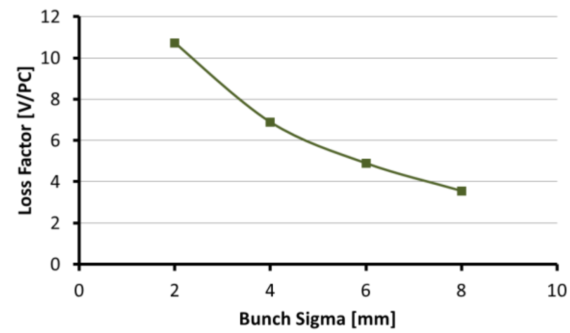


(a)

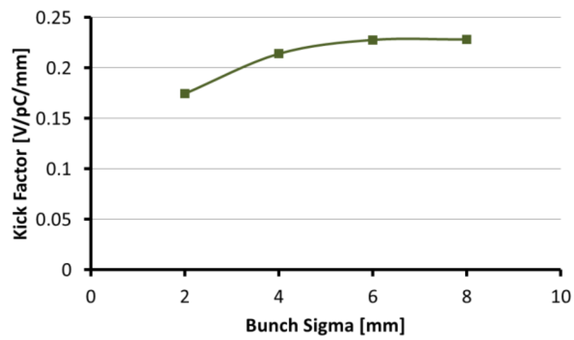


(b)

Figure 3: Wake potential for various bunch lengths. (a) Longitudinal. (b) Transverse.



(a)



(b)

Figure 4: Wakefield simulation results (a) Loss factor. (b) Kick factor.

$$L_{long} \cong \left\langle W^0_{long} \right\rangle = \frac{1}{Q}\int_{-\infty}^{\infty} W^0_{long}(s)q(s)ds$$
$$= \frac{1}{Q^2}\int_{-\infty}^{\infty}\int_{-\infty}^{s} w^0_{long}(s-s')q(s')q(s)ds'\,ds \qquad (1)$$

$$L_{trans} \cong \left\langle W^1_{trans} \right\rangle = \frac{1}{Q}\int_{-\infty}^{\infty} W^1_{trans}(s)q(s)ds$$
$$= \frac{1}{Q^2}\int_{-\infty}^{\infty}\int_{-\infty}^{s} w^1_{trans}(s-s')q(s')q(s)ds'\,ds \qquad (2)$$

where Q is the bunch charge, $q(s)$ is the longitudinal bunch distribution, W is the wake potential, and w is the wake function. However, the longitudinal and transverse wake functions at short distance s could be approximately related as [8]

$$w^1_{trans}(s) \cong \frac{2}{a^2}\int_0^s w^0_{long}(z)dz \qquad (3)$$

where a is the iris radius

In the periodic structure the short range wake can be approximated as [8]

$$w_{long}(s) = A\frac{Z_0 c}{\pi^2 a}\exp\left(-\sqrt{s/s_0}\right) \qquad (4)$$

$$w_{trans}(s) = \frac{2}{a^2}A\frac{Z_0 c}{\pi^2 a}2s_1\left(1-\left(1+\sqrt{s/s_1}\right)\exp\left(-\sqrt{s/s_0}\right)\right) \qquad (5)$$

Upon substituting for the wake potential in the loss factor and kick factor equation and assuming Gaussian charge we could reach

$$L_{long} = \frac{A_1}{\sigma^2}\int_{-\infty}^{\infty}\int_{-\infty}^{s}\exp\left(-\sqrt{(s-s')/s_0}\right)\exp\left(-\frac{s'^2}{2\sigma^2}\right)\exp\left(-\frac{s^2}{2\sigma^2}\right)ds'\,ds \qquad (6)$$

$$L_{trans} = \frac{4S_1}{a^2}\frac{A_1}{\sigma^2}\int_{-\infty}^{\infty}\int_{-\infty}^{s}\left(1-\left(1+\sqrt{(s-s')/s_1}\right)\exp\left(-\sqrt{(s-s')/s_0}\right)\right)\exp\left(-\frac{s'^2}{2\sigma^2}\right)\exp\left(-\frac{s^2}{2\sigma^2}\right)ds'\,ds \qquad (7)$$

Where A_1, S_0, S_1 are fit parameters.

Figure 5 shows the asymptotic approximation of the loss and kick factors based on the simulated data points calculated using CST microwave studio for relatively long bunches. In this perspective, the fit parameters for the loss factor are A_1=17 $V.mm^2/pC$ and S_0=0.5 mm, while the fit parameter for the kick factor is S_1=0.33 *mm* with an iris radius of a =15 mm.

Figure 5(a) demonstrates that the loss factor for a RMS bunch length of 50 μm is about 39.5 V/pC, increasing to 46 V/pC for a RMS bunch length of 10 μm. On the other hand, the kick factor decreases with decreasing the RMS bunch length as shown in Fig. 5(b), thus the kick factor is clearly not a concern for ultra-small bunches.

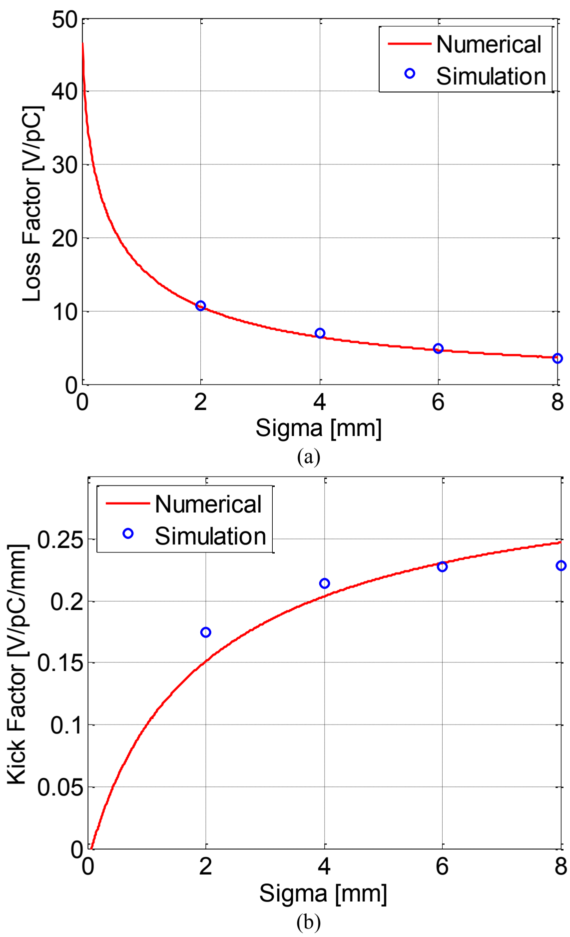


Figure 5: Asymptotic approximation (a) Loss factor. (b) Kick factor.

ESTIMATION OF CRYOGENIC LOSSES

Based on the aforementioned wakefield loss analysis, the cryogenic losses per cryomodule could be estimated as

$$L_{cyo} = nL_{long}QI$$

Where n is the number of cavities per cryomodule

For a particle beam of current 9 mA and charge 300 pC, the cryogenic losses of a four cavity cryomodule is listed in Table 1 for various bunch lengths.

Table 1: Cryogenic losses in W for a cryomodule of four cavities in case of beam current of 9 mA and beam charge of 300 pC.

Bunch RMS Length	Loss Factor [V/pC]	Cryogenic Losses [W]
8 mm	3.56	38.4
4 mm	6.89	74.4
2 mm	10.73	115.9
100 μm	35.1	379.1
50 μm	39.5	426.6
10 μm	46.5	502.2

CONCLUSION

Wakefield losses of the third harmonic 3.9 GHz elliptical cavity have been analysed. For relatively long bunches, the loss factor varies from 3.56 V/pC to 10.73 V/pC as the RMS bunch length decreases from 8 mm to 2 mm, while for ultra short bunches it reaches 46.5 V/pC for a RMS bunch length of 10 μm. The kick factor is not a concern for ultra-small bunches as it decreases with decreasing the RMS bunch length. The cryogenic losses for a cryomodule of four cavities would be 502.2 W for bunch RMS length of 10 μm, beam current of 9 mA and beam charge of 300 pC.

ACKNOWLEDGMENT

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