SURFACE ROUGHNESS WAKEFIELD MEASUREMENTS AT THE BROOKHAVEN ACCELERATOR TEST FACILITY

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Abstract

A surface roughness experiment was successfully carried out at the Brookhaven Accelerator Test Facility (ATF) to investigate the surface roughness wake-field effect on the electron beam. The energy loss and energy spread of the electron beam were characterized experimentally for four beam tubes with different surface roughness. All tubes are one meter long with 6 mm ID. No energy loss and energy spread increased observed for the regular pipe. The energy loss and energy spread increase as function of the electron beam bunch length were obtained for two pipes with periodic distribution of bumps. The bump depths for those two tubes are 0.3 and 0.6 mm, respectively. Those measurements agreed with the model predictions that includes both inductive impedance and synchronous mode. Energy spread induced by the fourth tube with randomly distributed bumps agrees only with the prediction of the inductive impedance model; and significantly less energy loss was observed from this tube. This is the first experimental observation of damping of the synchronous mode in a random distributed surface roughness tube, and it is in contradiction with the previous theoretical predictions.

1 INTRODUCTION

One of the major challenges for the proposed Linear Colliders and X-ray Free Electron Lasers (FEL) is to preserve the electron beam from the surface roughness wake-field effects induced by the long narrow beam tubes employed in such machines[1-2]. To understand the surface roughness wake field and its impact on the electron beam, several surface roughness wake field models were proposed by several groups recently [3-11]. Generally speaking, those models can be cataloged into two general models (or its combination), inductive impedance model and synchronous modes model. In the inductive impedance model, the total wake is considered to be the sum of collection of bumps with only inductive impedance [3-6]. For synchronous modes model, periodic distributions of bump is very much behaves like slow wave structure, it generates single mode running synchronously with the electron bunch [7]. Further more, a dielectric layer with an equivalent dielectric constant model was used to model surface roughness. The validity of those models depends strongly on the geometry of the surface bumps, and free parameters employed in the models. Surface roughness wake field for simple structure, such as a periodic structure with cylindrical symmetry can be calculated [8-10]. Due to the dramatic different predictions from different models, it is absolute critical to carry out experiment to verify those models. In the following sections of this report, the surface roughness wake field experiment at the ATF and its experimental results will presented.

The ATF is a user facility dedicated for beam physics R&D [11], and high-brightness electron beam produced by photoinjector and 70 MeV linac provides a unique opportunity for surface roughness wake-field experiment. Using the high-resolution electron beam energy spectrometer, we were be able to measure the electron beam energy loss and energy spread increase as functions of electron beam bunch length [12] for four different tubes. Significant less energy loss was observed for the random distributed bump beam tube, this is in contradiction with the previous theoretical predictions.

2 EXPERIMENTAL RESULTS AND ANALYSIS

2.1 Experiment Setup

The main objective of the surface roughness wake field experiment is to compare the experimental results with theoretical model predictions. The space available At the ATF can only accommodate one meter-long beam tube, and minimum bunch length for a minimum charge of 100 pC charge is about 1 ps (FWHM) [12]. To maximize the surface roughness wake field effect for such short beam tube and relative long electron beam bunch length (100 fs for XFEL), a relative low electron beam energy (40 MeV) and large artificially created large bump beam tubes were employed in our experiment. Therefore, larger-scale irregularities in the beam tube have to be artificially created in order to create measurable wakefield effects. Table 1 summarizes the basic properties of the four beam tubes used in the experiment. All beam tube is about 1 meter long with inner diameter (ID) 6 mm. A tapered transition was welded on each end of the all beam tubes to minimize the geometry wake field. The 1st beam tube has a regular smooth surface without any artificial corrugations and serves as a reference. The other three beam tubes are roughened with artificially bumps. The beam tubes 2 and 3 have periodic distributed bumps, and computer generated random distributed bumps were imprinted on the 4th beam tube. The height of the pumps for the 2nd beam tube is half that of the 3rd beam tube with the same base width. The 3rd and 4th beam tubes have the same size bumps.

The beam tubes were installed at the ATF beam line #2, the electron beam produced by the ATF accelerator system was transported to the beam tubes through 20 deg. achromatic double bending magnets. The dispersion range of this transport line was used to measure the electron beam energy and energy spread before the roughness tubes. A high resolution electron beam spectrometer located down stream of the beam tubes to measure the electron beam properties after the tubes. There is a beam profile monitor (BPM) at the each end of the beam tubes which capable of observing both electron and laser. An combination of the alignment laser and optical survey to insure the electron beam centered inside the beam tube within 50 µm, this will minimize the transverse wake field effect.

Table 1: Parameters of the beam tubes
(w and h are the width and height of bump, respectively)

Beam tube	Roughness	Total number	Distributed	Length (cm)
1st	Smooth	-	-	97
2nd	h=0.3 mm w=1.2mm	~3240	Regularly	97
3rd	h=0.6 mm w=1.2mm	~3240	Regularly	97
4th	h=0.6 mm w=1.2mm	~2900	Randomly	97

2.2 Experimental Results and Analysis

The 1st normal beam tube was first installed in the beam line. There is observable beam energy loss or energy spread increase within the spectrometer resolution (0.05%). This shows the resistive wall and surface roughness (short, normal finish) wake fields are negligible for our experiment.

The 2nd and 3rd beam tubes with periodic distributed bumps to mimic the surface roughness were then each installed in the beam line, respectively. In practice, the tube surface roughness is not perfect regularly distributed corrugations, but exhibits random protrusions. Such a random nature results in some de-coherence of the induced fields, but the synchronous mode may still exist there. The 4th tube with randomly distributed bumps was used to compare with the 3rd tube, and to study the de-coherence of the synchronous mode due to the random distribution.

For the photocathode RF gun, both the electron beam pulse length and its charge are the functions of the RF gun phase. The electron bunch length variation was implemented in our experiment by the varying the RF gun phase [12]. For the sake of easy comparison, all of measured data were normalized to 1 nC charge since the energy loss and energy spread caused by the surface roughness wakefield is the linearly proportional to the charge. Figure 1 plotted energy spread as function of the electron beam bunch length after normalization for three beam tubes. The normalized energy loss as a function the electron beam bunch length for the three tubes is shown in Figure 2. The fit of the experimental data using different models are also shown in both figure 1 and 2. Figure 2 shows that, the energy loss due to the surface roughness wake field for the random beam tubes is significantly less than that for the periodic beam tube with the same bump size. This is the first experimental observation of the de-coherence of the synchronous mode.

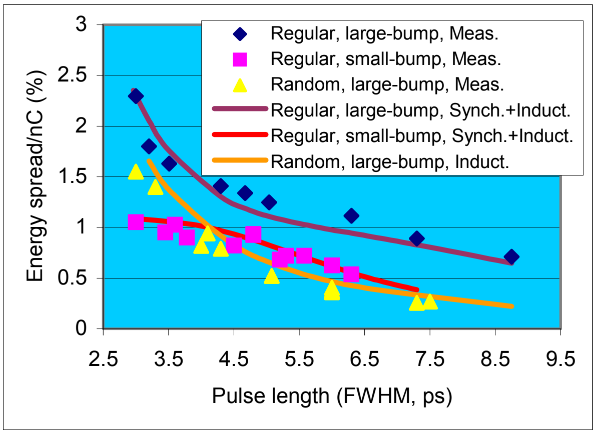

Figure 1: Energy spread of rough beam tubes

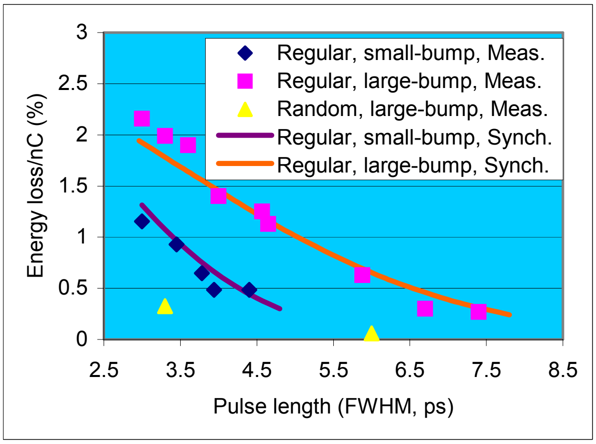

Figure 2: Energy loss of rough beam tubes

In the rest of this section, we will discuss the models used to fit the experimental data. Since the bump size is smaller than the bunch length, the behavior of the individual bump is inductive. For the inductive impedance model, it was assumed that a rough surface can be represented as a collection of bumps of relatively simple shapes on a smooth surface, and the total impedance can be approximated as the sum of the impedance of the individual bump. For individual ellipsoidal or hemisphere protrusion on the surface of a beam tube with radius b, its impedance can be expressed with (g, h is smaller than b) [5]:

$$Z = -i\frac{Z_0 khg^2}{6\pi b^2}\left\{ I_1^{-1}\left(\frac{h}{g}\right) + \left[I_2\left(\frac{h}{g}\right) - 1\right]^{-1}\right\} = -i\omega L \qquad (2)$$

where g, h are the width and height of the ellipsoid, respectively (g=h for hemisphere protrusion), Z_0 is impedance in the free space, k is the wave number, L is the inductance and

$$I_n(x) = \frac{x}{2}\int_0^\infty \frac{d\xi}{(\xi+1)^n\left(\xi+x^2\right)^{\frac{5}{2}-n}} \qquad (3)$$

For a beam tube with length of $L_{tube,}$, the accumulated absolute energy spread at the end of the beam tube is:

$$\delta E_{rms} = \frac{Ne^2 L_{total} L_{pipe} c^2}{3^{3/4}\sqrt{2\pi}\sigma_z^{\ 2}} \qquad (4)$$

Here Ne is the bunch charge, L_{total} is the inductance per unit length, c is the speed of light, σ_z is the rms bunch length. Since the impedance is inductive, no energy loss is predicted with this model. Substituting the parameters of the 2nd, 3rd and 4th tubes into above equations, the inductive impedance contributions to energy spread are shown in Figure 1. Figure 1 shows that the measured energy spread in the 2nd and 3rd tubes is more than the prediction by the inductive impedance model but the measured energy spread in the 4th one agrees well with the prediction by the inductive model. In addition, energy loss in the 2nd and 3rd tubes are easily observable, it is significantly reduced for the 4th tube. This implies that the synchronous modes may exist in the tubes with regularly distributed bumps, but do not survive in the tube with randomly distributed bumps. So the randomization of the locations of the bumps destroys the coherent buildup of radiated waves and the induced fields decay rapidly.

The analytical equations [8-10] can be used to estimate the synchronous modes for cylindrically symmetrical periodic corrugations. The wake function is given by,

$$w(s) = \frac{Z_0 c}{\pi b^2}\sum_n F_n \cos\left(\frac{\omega_n s}{c}\right) \qquad (5)$$

where s is the distance from the bunch head, ω_n is the frequency of the synchronous mode. F_n is the coupling coefficient of the n^{th} mode. For the 2nd and 3rd tubes, the bump distribution is interleaved though regular. Based on the experimental result of the energy loss, we found that a single resonant mode fits the data well. This mode can be regarded as the lowest mode of a dielectric tube [7]. The corresponding effective dielectric constant is obtained by solving the dispersion relation. Using this effective dielectric constant we could then find the coupling coefficient F_0 of this fundamental mode. So the corresponding wake function becomes

$$w(s) = \frac{Z_0 c}{\pi b^2} F_0 \cos\left(\frac{\omega_0 s}{c}\right) \qquad (6)$$

The synchronous model not only predicts energy spread, energy. Using the fitted frequencies 0.76 THz and 0.47 THz for synchronous model, and combining with inductive model, both measured energy spread and energy loss for 2nd and 3rd beam tubes agreed with the models. The coupling coefficient is 0.552 for the tube with large bumps, and 0.676 for the one with small bumps. Since the bump height is not negligible with respect to the tube radius, we solve the dispersion relation directly to get the dielectric constant. In our case, we get $\varepsilon = 1.54$ for the tube with larger bumps, and 1.37 for the one with smaller bumps. This is slightly different from the thin layer limit, which gives a formula of:

$$k_0 = \sqrt{\frac{2\varepsilon}{(\varepsilon - 1)bh}} \qquad (7)$$

If we use this formula, we will get $\varepsilon = 1.82$ for the 2nd and that for the 3rd tube is 1.52.

3 CONCLUSION

The energy loss and energy spread for four beam tubes (one is regular smooth tube and other three are with artificially made bumps) were characterized experimentally at the ATF. For the cases of periodic distributed bumps, the experimental results show one single synchronous mode exists in the surface roughness and interacts with the electron beam, in addition to the inductive impedance. For the tube with randomly distributed bumps, the measured energy spread agrees well with the prediction by the inductive impedance model only. A significantly less energy loss observed is the first observation the de-coherence of the synchronous mode from random distributed bumps. The synchronous modes decay in the random bumps is in contradiction with the theoretical predictions [13] and earlier experimental observation [14].

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REFERENCES

[1] *TESLA Technical design report*, DESY, Germany, 2001.
[2] *LCLS CDR*, SLAC, USA, 2002.
[3] K.Bane, *et al.*, SLAC-PUB-7514, 1997.
[4] G.Stupakov, *et al.*, Phys. Rev. ST Accel. Beams 2, 1999.
[5] G.Stupakov, Phy. Rev. ST, 1, 1998.
[6] K.Bane and G.Stupakov, SLAC-PUB-8023, 1998.
[7] A.Novokhatski, *et al.*, PAC97, Vancouver, 1997.
[8] K.Bane and A.Novokhatski, LCLS-Tech. Note 99-1, 1999.
[9] G.Stupakov, SLAC-PUB-8743, 2000.
[10] F.E.Borgins *et al.*, Enc. Of Physics XXI, 1950.
[11] I. Ben-Zvi *et al.*, NIM A304, 1991.
[12] X.J. Wang *et al*, Phys.Rev. **E 54**, R3121-3124 (1996).
[13] A.Novokhatski *et al* Proc. of ICAP98, Monterey, September 1998, also as DESY preprint, TESLA 99-17 (1999), DESY, Hamburg, Germany.
[14] M.Huening, H.Schlarb, P.Schmueser, *et al.*, Phys. Rev. Lett. 88, 074802 (2002).