Roughness Tolerance Studies for the Bypass Line in LCLS-II

LCLS-II TN-18-03

7/17/2018

Y. Ding, K. Bane, and G. Stupakov

SLAC, Menlo Park, CA 94025, USA

Abstract:

In this note we evaluate the roughness wakefield effect in the LCLS-II bypass line. The motivation is that some recently received drift pipes have surface roughness that is out of the specified tolerances. Based on surface roughness measurements taken on samples from the existing pipes in the bypass line and from newly fabricated ones, we see the existing pipes have good surface smoothness, while the new ones are a factor of two worse than the initial tolerance requirements. We find that, for the existing pipes, the wakefield contribution of roughness is negligible; for the new pipes with 500-m long, the relative energy loss induced at the bunch tail (for the 300-pC case with 1-kA current) is 0.17% for resistance plus roughness, vs. 0.14% for resistance without roughness; the roughness adds about a 20% effect on the chirp variation. There is barely any effect for the 100-pC case which has a shorter bunch. We consider these new pipes acceptable.

1 Introduction

In the LCLS-II, after acceleration and compression, short bunches, with a maximum energy of 4 GeV, pass through a ~2.5 km-long, round stainless steel (SS) pipe of radius 24.5 mm—bypassing the existing copper linac for LCLS-I and FACET—on their way to the undulator. The longitudinal wakefield in the bypass line vacuum chamber induces added energy variation (energy chirp) along the bunch. In the bypass pipe the wakefield is primarily due to the resistance in the chamber walls [1], and since the final bunch is short and approximately uniform, the wake-induced chirp is rather linear. In the system design for LCLS-II this effect is actually made use of, to remove residual energy chirp left in the beam before the undulator (to “dechirp” the beam). In Ref. [1] it was concluded that for both the nominal (100 pC) and high bunch charge (300 pC) cases of LCLS-II, the resistive wall wakefield of the long bypass line works well to remove the residual energy chirp.

There is also another contribution to the wakefield of a chamber such as the bypass pipe: the roughness of the vacuum chamber surface. To minimize the impact of the pipe wake, one would like a wall surface smooth enough so that the roughness component of the wake is a small fraction of the total wake (say ≤ 20%). In Ref. [2] the roughness tolerance for the undulator chamber, where the full vertical aperture is 5 mm, was carefully studied. In the present note, we follow a similar procedure as was done in [2], in order to estimate the surface roughness effect in the long bypass line in LCLS-II. The bypass line consists of ~2 km of existing pipe and ~500 m of new pipe. Parts of the new pipe that were recently received from one vendor had a surface roughness that is out of the tolerances specified, which is the motivation for the present study. Here we would like to estimate the importance of the extra pipe roughness for LCLS-II, to see if it is significant.

2 Wakefield calculation with surface roughness

We follow the same formulas as in [2] to evaluate the roughness effect. Since the resistive-wall wake is always there, we estimate the relative contribution that the roughness component adds to the induced energy variation in the LCLS-II bunch. The total bypass line of 2.5 km as mentioned above includes two sections in terms of our calculations: (1), the existing PEP-II high energy ring (HER) bypass line, which is about 2 km long; (2), the new fabricated drift pipes, which will reach from the Sector 30 area to the undulator entrance, a distance of about 500 m.

For the LCLS-II bypass line, the beam pipe radius a = 2.45 cm; for SS, conductivity $\sigma_c = 1.4 \times 10^6\ \Omega^{-1}m^{-1}$ and ac relaxation time $\tau_c = 8$ fs. We consider the worst case that has a bunch charge of 300 pC with peak current of 1 kA (a uniform distribution with total length of 90 µm), and the beam energy is 4 GeV. The roughness model we use consists of small, shallow, sinusoidal corrugations [2]. For example, the wall profile radius r is assumed to vary sinusoidally with longitudinal position z: $r = h \cos \kappa z$, where h is the amplitude of the corrugations, and $\kappa = 2\pi/\lambda$ with λ the corrugation period.

The measurement of the pipe surface roughness was performed with a roughness instrument from Mitutoyo [3]. The roughness profile along the z direction (the axis of the pipe) can be measured. For the drift pipes with flanges, only a few mm into the pipe from the two ends can be measured. The measurements include two sample pipes from the existing PEP-II HER line, and 20 new pipes (with two measured roughness profiles) [4]. Analyzing the measurement data, we obtain the surface roughness period of the new pipes to be about 100 - 300 µm, with mean roughness value Ra ~3 µm (we use this value as the amplitude of the corrugations h in our calculations). For the existing bypass line, the surface roughness period is about the same, but with a lower mean roughness value Ra ~0.5 µm. Note that the initially required surface roughness tolerance is 63 µinch (~1.6µm). Clearly, we can see that the new pipes have worse surface roughness and we will evaluate the effect.

We follow the methods in [2] to calculate the wakefield induced relative voltage change in a uniform bunch, with peak current of 1 kA and beam energy of 4 GeV. For the 500 meters of new pipe, we take $\lambda = 100$ µm, h = 3.2 µm in the surface roughness model according to the measured data. This mean roughness value is a factor 2 worse than the initial tolerance requirement. In Figure 1, we show three cases of the calculated induced voltage change along the bunch: (1) due to roughness only; (2) due to the resistive wall only; (3) due to the combined effect of both resistive wall and the roughness. Note that the total impedance is not a simple summation of the two contributions, as was discussed in [2].

As can be seen in Figure 1, for the pipe size and bunch parameters used in the LCLS-II, the roughness will add significant energy loss only at the bunch tail. With the 500 m of new pipes, when considering both the resistive wall and roughness wakes, the relative energy loss induced at the bunch tail (in the 300 pC case) is 0.17% for resistance plus roughness, vs. 0.14% resistance only without considering roughness; the

roughness would add a ~20% effect to the induced energy loss but only at the tail of the 300-pC bunch. This effectively changes the beam chirp on the tail side by 20% (enhances the "dechirp" effect), while there is barely any effect to the 100-pC bunch which has a shorter bunch length at the same 1-kA current. The bunch length is marked in Figure 1 for 100 pC and 300 pC, respectively.

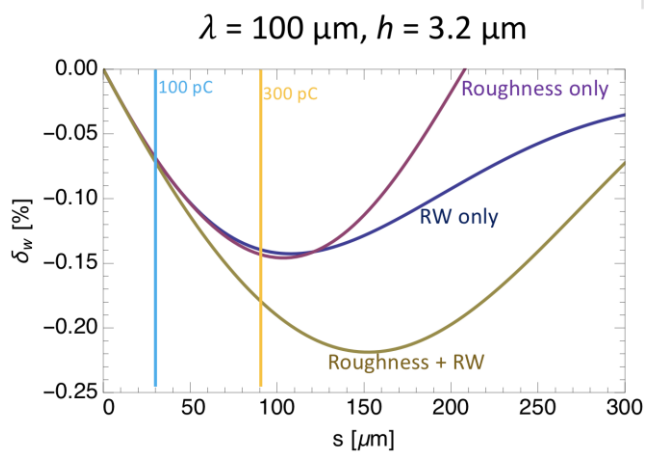

Figure 1: The relative induced voltage along a bunch with a uniform distribution, for the case of a 500-m long pipe that has resistance only (blue), roughness only (red), and both resistance and roughness (brown). The resistive wall calculation includes ac conductivity for SS, with pipe radius 2.45 cm; the roughness model assumes a corrugation period of 100 µm with h = 3.2 µm. The beam has a uniform distribution with its head located at s = 0. The beam peak current is 1 kA, and the beam reaches to 30 (90) µm for charge 100 (300) pC. The beam energy is 4 GeV.

For the existing ~2 km bypass line, with the measured mean roughness value Ra ~0.5 µm, the wakefield from roughness is negligible comparing to resistive wall wakes for a bunch charge of 300 pC or lower. For this situation, the roughness induced wake effect comes only from the last 500 m pipe, while the resistance of the walls comes from all 2.5 km of pipe. For a total 2.5-km long pipe, the resistive-wall induced relative energy loss at the bunch tail of 300-pC bunch is about 0.7%; when we include the roughness effect of the last 500 m pipe, the total relative energy loss from both resistance and roughness would be 0.75% at the bunch tail of the 300-pC bunch.

3 Conclusions

Because the last section of about 500-m long new pipe has surface smoothness worse than the initially specified tolerance, we checked the wakefield effect based on measured surface roughness data. With a factor of two increase in roughness amplitude (from 63 µinch to 126 µinch), the roughness component of wakefield adds ~20% to the wake-induced energy loss at the bunch tail (for the case of 300-pC bunch charge). Fortunately, the existing 2-km bypass line has good surface smoothness, which helps reduce the relative effect when we compare the roughness wake from the 500-m new pipes to the overall 2.5-km long resistive wall wakes. We consider these new pipes acceptable.

Reference:

[1] K. Bane and T. Raubenheimer, "Wakefield effects of the bypass line in LCLS-II", LCLS-II TN-14-09.

[2] K. Bane and G. Stupakov, "Roughness tolerance studies for the undulator beam pipe chamber of LCLS-II", LCLS-II TN-14-06.

[3] https://www.mitutoyo.com/wp-content/uploads/2012/11/1984_Surf_Roughness_PG.pdf, reference manual of the instrument.

[4] Private communications with Georg Gassner and Mike Gaydosh.