

Wake fields and energy spread for the ERHIC ERL

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Abstract

Wake fields in high-current ERLs can cause significant beam quality degradations. Here we summarize effects of coherent synchrotron radiation, resistive wall, accelerating cavities and wall roughness for ERL parameters of the eRHIC project. A possibility of compensation of such correlated energy spread is also presented. An emphasis in the discussion is made on the suppression of coherent synchrotron radiation due to shielding and a possible reduction of wall roughness effects for realistic surfaces.

INTRODUCTION

In this report we discuss the wake fields with a focus on their effect on the energy spread of the beam. Other effects of wake fields are addressed elsewhere. An energy spread builds up during a pass through a very long beam transport in the eRHIC ERL under design [1]. Such energy spread become important when beam is decelerated to low energy, and needs to be corrected.

Several effects, such as Coherent Synchrotron Radiation (CSR), Resistive Wall (RW), accelerating RF cavities (RF) and Wall Roughness (WR) were considered. In this paper, we briefly summarize major contributions to energy spread from the wake fields for eRHIC parameters, and present possible energy spread compensation for decelerated beam. In the rest of the report we discuss effects which we believe are suppressed for the eRHIC parameters.

SOURCES OF ENERGY SPREAD FOR ERHIC ERL

For the eRHIC project, electron beam with high peak current has to go through the present tunnel of the Relativistic Heavy Ion Collider (RHIC) 6 times to reach the top energy (at which electron beam will collide with the ion beam) and then additional 6 times to be decelerated before going to the dump. To save on the cost of the vacuum chambers and magnets very small aperture of vacuum chambers are considered. As a result, such effects as RW and WR are strongly enhanced.

For the first stage of the eRHIC, the maximum top energy is presently 5 GeV, for the second stage the energy is upgradable to 20 and 30 GeV by adding additional RF cavities. For the second stage of the eRHIC, the highest bunch current is for 20 GeV energy. In Figs. 1 and 2 we show total longitudinal wake potential for the 5 GeV and 20 GeV scenarios for parameters shown in Tables 1 and 2, respectively. Table 3 shows summary of major contributions to the energy spread for the 20 GeV case.

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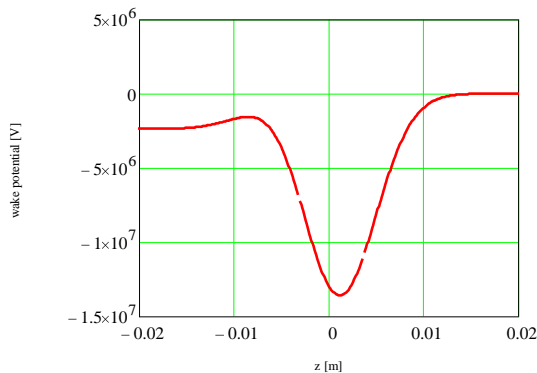


Figure 1: Longitudinal wake potential (contribution from RF cavities and Resistive Wall) for 1st stage 5 GeV eRHIC parameters in Table 1.

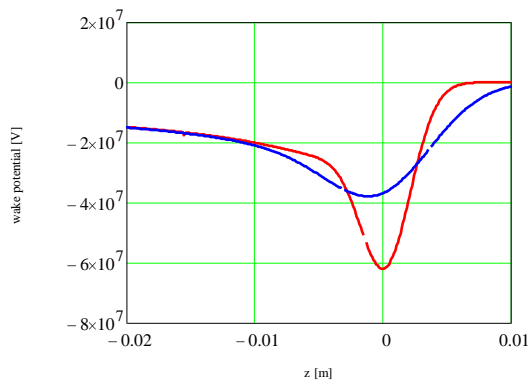


Figure 2: Longitudinal wake potential (contribution from RF and Resistive Wall) for 20 GeV eRHIC parameters in Table 2 for rms bunch length of 4 mm (red) and 2 mm (blue).

Table 1: Beam parameters used for 1st stage 5 GeV eRHIC ERL.

Total length of beam transport (12 passes), km	46
Bunch charge, nC	3.5
Beam pipe diameter (low-energy passes), mm	8
Beam pipe diameter (high-energy passes), mm	5
Total number of RF cavities per pass	48
Rms bunch length, mm	4

Table 2: Beam parameters used for 20 GeV eRHIC ERL.

Total length of beam transport (12 passes), km	46
Bunch charge, nC	3.5
Beam pipe diameter (low-energy passes), mm	8
Beam pipe diameter (high-energy passes), mm	5
Total number of RF cavities per pass	240
Rms bunch length, mm	2-4

Table 3: Total wake field contribution to the energy spread for the 20 GeV eRHIC for rms bunch length of electron beam 2 mm.

	Energy loss, MeV	Rms energy spread, MeV
CSR	suppressed	suppressed
Resistive wall	14 (Aluminum)	14.7
RF cavities	36	14.4
Wall roughness	suppressed	< 2

In this paper all values are shown for the Gaussian longitudinal distribution of electron beam. In Figs. 1-2 and Table 3, it is assumed that contribution from CSR and WR is suppressed. Such assumptions are discussed in the following sections.

The resulting energy spread is too large, even for the case of 1st stage 5 GeV eRHIC (+/-6.7 MeV) for which longer bunch length with 4 mm rms was already chosen, to go through the final low-energy beam transport to the dump. In the absence of various decoherence effects, such as synchrotron radiation or intrabeam scattering, for example, one can assume that accumulated energy spread is well correlated and thus its correction could be possible. In Fig. 3, we show an example of such correction for the 5 GeV case. The correction is done after beam is decelerated to 100 MeV energy and goes into eRHIC injector. The beam is first stretched by introducing longitudinal dispersion of 0.3 m with a subsequent adjustment of the phase of the injector linac. The resulting energy spread at 10 MeV is +/-3.7 MeV (green line in Fig. 3) and could be already satisfactory to go all the way to the dump. Compensation of energy spread for the 20 GeV eRHIC (which is significantly larger, as shown in Fig. 2) is under study and will be reported elsewhere.

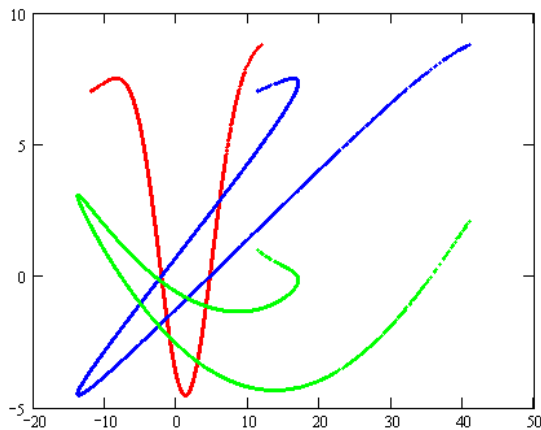


Figure 3: Compensation of correlated energy spread for 5 GeV eRHIC. Horizontal axis: longitudinal position within the bunch in mm; vertical axis – energy in MeV. Red – initial wake potential; blue – after stretching the beam; green – after adjusting the phase of the injector linac.

CSR SHIELDING

Simple estimates of CSR effect for eRHIC shows that electron beams would have significant energy spread and energy loss if one does not take into account the shielding effect of the beam pipe walls. However, when the walls of vacuum chamber are conducting, induced charges will decrease the EM fields created directly by the bunches. This phenomenon is known as shielding of CSR and is the stronger the closer the induced charges. Analytic theory of CSR shielding suggests that CSR can be suppressed if beam-pipe dimension is small or the bunch length is large. A suppression factor involves bunch length, pipe dimension and radius of the curvature and is different for energy loss and energy spread suppression.

Theoretical studies of shielding goes back to the work by Schwinger [2] with subsequent work by many others starting with Ref. [3]. In accelerator community analytic expressions for the coupling impedance of vacuum chambers of various geometries for a particle moving on a circular orbit were obtained by Warnock [4]. A simplified form for the coupling impedance was given, for example, in Ref. [5]. In terms of the wake functions closed form expressions were derived in Ref. [6]. A direct summation of image charges was recently used in Ref. [7], which showed suppression of both energy loss and energy spread but by a very different degree. Such a different degree of suppression of the energy loss and energy spread follows directly from the closed form expression for the impedance as well [5], which has both real and imaginary parts. One can see that the real part of the impedance has very strong exponential suppression while the imaginary part does not, and thus less suppression is expected for the energy spread than for the energy loss.

For the eRHIC parameters the bunch length of electron beam is relatively long, and estimates based on the expression for the coupling impedance from Ref. [5] show that both energy loss and energy spread due to CSR will be completely suppressed for present vertical size of the vacuum chamber of 5 mm, due to a very large suppression factor.

Until recently [7], shielding of CSR was mostly discussed with regard to the suppression of the power or energy loss rather than its effect on the energy spread of the beam. Also, no experiments which directly address effect of shielding on the energy spread was found. Therefore, to address this question experimentally, a series of dedicated measurements of shielding of CSR were recently performed at BNL's Accelerator Test Facility which observed suppression of both CSR-induced energy loss and energy spread [8].

WALL ROUGHNESS

Contribution of WR to the coupling impedance (wake potential) can become important especially when the size of the vacuum chamber is small and length of the electron bunch is very short. Several theoretical models were developed in the past which showed rather different importance of this effect. Some experimental studies of

the wall roughness are also available. Here we briefly review the models and discuss their application to realistic surface roughness.

An effect of the wall roughness was first estimated based on the impedance of small protrusions of different configurations and orientations [9]. In this model, impedance is purely inductive and thus there is no effect on the energy loss, just on the energy spread. Such a model is referred to as “inductive”. The inductive model was first used to estimate the wall roughness effect for the LCLS design which set very strict requirements on the surface polishing since the effect was estimated to be very strong. However, for realistic surfaces the length of the protrusions is significantly larger than their height, and thus the impedance is reduced (similar to the impedance of a long slot vs. impedance of a hole). As a result, an estimate based on this model gives result which overestimates the impedance and imposes over conservative tolerances in terms of the rms height of the roughness.

The length of the protrusions along the surface (referred to as the “correlation length”) was taken into account in a model developed by Stupakov [10], which reduced the coupling impedance significantly for typical surfaces with large correlation length. Such model is referred to as “statistical”. Its comparison with “inductive” model was given in [11]. Discussion and measurement of the surface roughness as well as arguments that the “statistical” model is a better description of realistic wall surfaces can be found in Ref. [12], for example.

Another model for the wall roughness was introduced by Novokhatski [13, 14]. In this model the presence of roughness is equivalent to a pipe with a thin dielectric layer or periodic corrugation on the smooth wall surface. This model is referred to as the “resonator” model. In the resonator model the coupling impedance has also resistive part. As a result, one may need to worry about energy loss in addition to the energy spread.

A detailed comparison of the “resonator” and “inductive” models was given in [14]. Estimates done with the resonator model can result in even stronger effect from the wall roughness especially if the bunch length is small or comparable to the length of the protrusion (period of corrugation) or the longitudinal profile of the bunch is not smooth. The resistive part of the impedance is associated with the mode which can be excited by the beam and can propagate synchronously with the beam (“synchronous” mode). However, the model becomes invalid when the correlation length (or period of corrugation) is significantly larger than the height of the protrusion.

An extension of the theory to shallow corrugations showed that the low-frequency synchronous mode becomes suppressed for the large aspect ratios of the correlation length to the height of the protrusion, as shown in a subsequent work by Stupakov [15, 16].

In addition to theoretical models of the wall roughness, dedicated experimental studies were conducted as well. In Ref. [17] existence of the synchronous modes was

confirmed, while in Ref. [18] suppression of the synchronous modes was demonstrated for the surface roughness with large aspect ratios, in agreement with theory [16] and numeric simulations [19].

For the present estimate for the eRHIC, we thus assume that suppression of the synchronous modes will occur for large aspect ratios of the wall roughness, and that we can use expression from Ref. [16] to calculate the suppression factor for our parameters. To minimize the wall roughness effect we would also like to have a vacuum chamber surface with the aspect ratio of the wall roughness as large as possible. Therefore, extruded aluminum vacuum chambers were suggested for the eRHIC design.

Since we were not able to find measurements for extruded aluminum surfaces with a detailed characterization of the wall roughness, we attempted such measurements ourselves [20]. For these measurements, a small sample of an unpolished extruded aluminum NSLS-II vacuum chamber was used. Using commercial “PocketSurf-1” device, measured rms height of the groves on the surface was about 3-4 microns, which is slightly higher than in similar measurements done at NSLS-II [21]. The measurements of the correlation length were done at BNL’s Instrumentation Division using an optical microscope which gave about 3 mm length for such waves/groves in the direction of extrusion.

Using measured aspect ratio of 3000/3 (length to height) for the wall roughness, the suppression factor from Ref. [16] is $3 \cdot 10^{-10}$ for design parameters of eRHIC. Therefore, we assume that there should be no energy loss due to the suppression of the low-frequency synchronous mode for our parameters. However, for such long protrusions the bunch length is no longer larger than the correlation length, and thus excitation of high-frequency synchronous modes may need to be considered. On the other hand, experimental study in Ref. [18] seems to indicate suppression of the synchronous modes even for this regime of parameters.

The large aspect ratio of the roughness also suppresses inductive part of the impedance thus decreasing energy spread due to the wall roughness. As an example, Fig. 4 shows resulting energy spread due to the wall roughness for the eRHIC design calculated using expression from Ref. [10] where long correlation length is taken into account.

Based on this estimate, for our parameters with the vacuum chamber full size of 5 mm, expected contribution to the energy spread appears to be less important than from the RF and RW effects. As a result, we presently do not impose additional requirement of polishing of the vacuum chambers to a high degree. If needed, the effect of the wall roughness can be further minimized by increasing bunch length and increasing the size of the vacuum chamber.

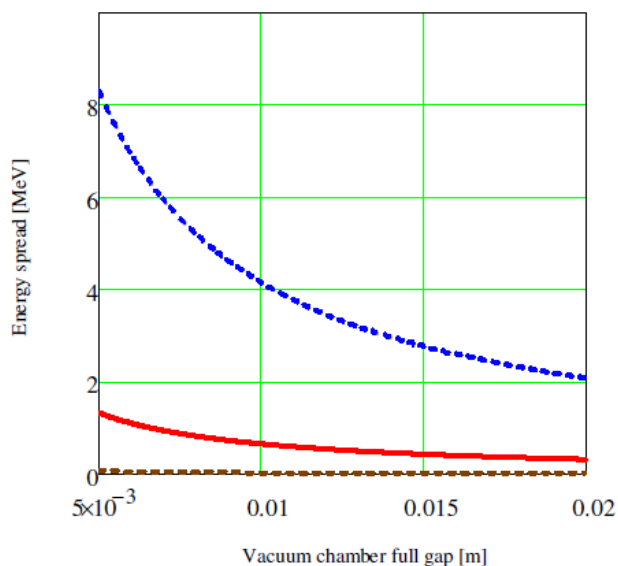


Figure 4: Calculated energy spread due to wall roughness for eRHIC design (for rms bunch length of 2 mm) assuming measured correlation length of 3 mm for several rms heights of the wall roughness: Blue (dashed upper curve) – 10 μm ; red (solid middle curve) – 4 μm ; brown (dashed low curve) – 1 μm .

As discussed in this section, wake fields due to the wall roughness can have a very strong effect on the eRHIC design depending on the assumption used. Our present understanding of the subject, and assumptions used, suggest that this effect may be mitigated with the vacuum chamber surface which has very large aspect ratios of the wall roughness. However, discussion presented here should be regarded as work in progress, and further studies of this subject will continue.

SUMMARY

For the eRHIC design, effect on the energy spread from the longitudinal wake fields was estimate from the RF cavities, Resistive Wall, Coherent Synchrotron Radiation and Wall Roughness. The largest contribution comes from the RF cavities and resistive wall.

Most of the discussions in this report were devoted to the effects which appear to be less settled such as suppression of CSR due to shielding and possible suppression of WR effects for surfaces with the large aspect ratios of the roughness.

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