WAKE FIELDS EFFECTS FOR THE ERHIC PROJECT*

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Abstract

An Energy Recovery Linac (ERL) with a high peak electron bunch current is proposed for the Electron-Ion collider (eRHIC) project at the Brookhaven National Laboratory. The present design is based on the multi-pass electron beam transport in existing tunnel of the Relativistic Heavy Ion Collider (RHIC). As a result of a high peak current and a very long beam transport, consideration of various collective beam dynamics effects becomes important. Here we summarize effects of the coherent synchrotron radiation, resistive wall, accelerating cavities and wall roughness on the resulting energy spread and energy loss for several scenarios of the eRHIC project.

SOURCES OF ENERGY SPREAD FOR ERHIC ERL

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

In the most recent eRHIC design, electron beam with high peak current has to go through the present RHIC tunnel and accelerating linacs 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 apertures of the vacuum chambers are considered. As a result, such effects as resistive wall (RW) and wall roughness (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 RF cavities. For the second stage of the eRHIC, the highest bunch current is for the energy of 20 GeV, limited by the synchrotron radiation.

Figures 1 and 2 show dominant contributions to the wake potential for the 5 and 20 GeV scenarios for parameters shown in Tables 1 and 2. Figures 3 and 4 summarize accumulated energy spread for the 5 and 20 GeV, respectively. An expected suppression of the coherent synchrotron radiation (CSR) due to the vacuum chamber shielding effects and a possible reduction of the wakes from the wall roughness for the eRHIC parameters is discussed in detail in Ref. [2].

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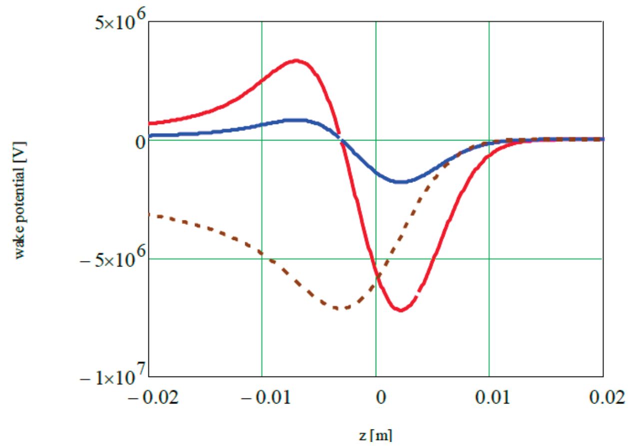

Figure 1: Longitudinal wake potential (for Gaussian bunch moving to the right) for 1st stage 5 GeV eRHIC parameters in Table 1: 1) from RF cavities: brown dash line; 2) resistive wall: red – from passes with 5 mm chamber gap; blue – from passes with 10 mm full gap.

Table 1: Beam parameters used for the first 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	10
Beam pipe diameter (high-energy passes), mm	5
Total number of RF cavities per pass	48
Rms bunch length, mm	4

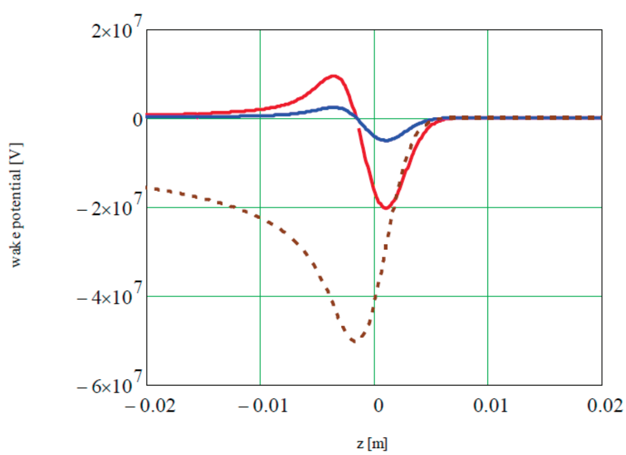

Figure 2: Longitudinal wake potential for 20 GeV eRHIC parameters in Table 2: 1) from RF cavities: brown dash line; 2) resistive wall: red – from passes with 5 mm chamber gap; blue – from passes with 10 mm full gap.

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	10
Beam pipe diameter (high-energy passes), mm	5
Total number of RF cavities per pass	240
Rms bunch length, mm	2

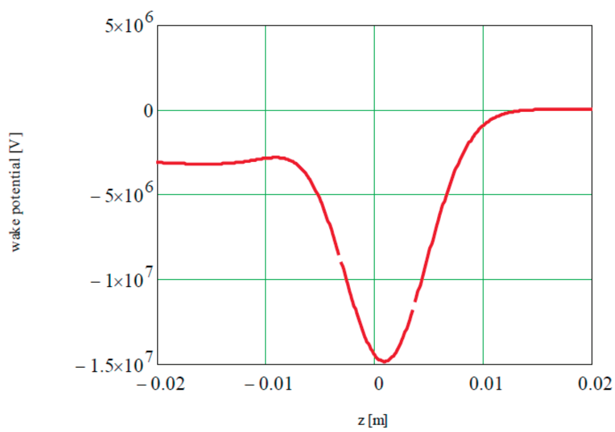

Figure 3: Energy spread from RF cavities and resistive wall for the 5 GeV eRHIC parameters in Table 1.

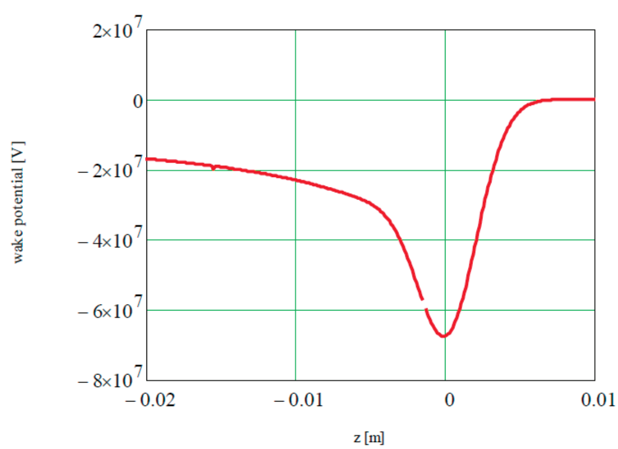

Figure 4: Energy spread from RF cavities and resistive wall for the 20 GeV eRHIC parameters in Table 2.

Table 3: Contributions to the energy spread for the 20 GeV eRHIC (full energy scenario with the highest peak current [1]) for the rms bunch length of 2 mm.

	Energy loss, MeV	Rms energy spread, MeV
CSR	Suppressed	Suppressed
Resistive wall	12 (aluminum)	12.3
RF cavities	35	16.3
Wall roughness	Suppressed	under study

For the first stage 5 GeV eRHIC, accumulated correlated energy spread from the RF cavities and RW is ± 7.2 MeV (rms 4 MeV) with the energy loss of 9 MeV. For the 20 GeV case, accumulated energy spread is ± 34 MeV with the energy loss of 47 MeV. Such a large energy spread requires special energy correction approach which is being considered.

For the eRHIC parameters, the bunch length of electron beam is relatively long, and analytic estimates show that both the energy loss and energy spread due to the CSR will be completely suppressed by the shielding effect of the vacuum chambers [2]. In addition, experiments which confirmed suppression of the CSR-induced energy spread by shielding were conducted at BNL's Accelerator Test Facility (ATF) [3].

An estimate of contribution from the wall roughness effect strongly depends on assumptions about the surface characteristics. As discussed in Ref. [2], with a choice of extruded aluminum for the vacuum chambers we expect substantial reduction of the wall roughness effects. However, recent measurements of extruded aluminum surface [4] suggest that effects from the wall roughness may be still significant for the eRHIC parameters. To address this question and to come up with a practical requirement on the wall roughness, a dedicated experiment of the wake fields from the wall roughness at BNL's ATF is being considered [5].

WAKE FIELD FROM RF CAVITIES

For an estimate of various effects, including dependence on the longitudinal density distribution, it is convenient to use an analytic expression of the wake function. For this purpose, we have used the wake function of a single pillbox cavity. A high-frequency approximation of such wake (Eq. 1) is in good agreement with the wake calculated numerically using ABCI code for the actual 5-cell structure of BNL-3 SRF cavity, as shown in Fig. 5. This enabled us exploration of wake potentials and resulting energy spread for different longitudinal density distributions.

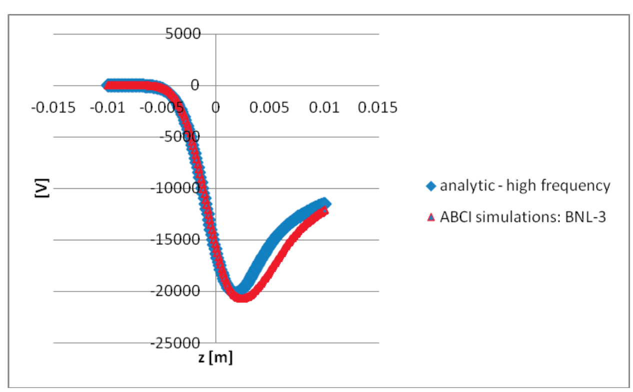

Figure 5: Wake potential for a 5-cell BNL-3 SRF cavity for a Gaussian bunch with 2 mm rms length and 3.5 nC charge moving to the left.

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The high-frequency approximation of the wake function of a pillbox cavity is given by

$$W_{rf}(s) = k_1 \frac{2\sqrt{2g}}{b\pi} \frac{1}{\sqrt{s}}, \quad (1)$$

where b is the beam pipe radius and g is the length of the pillbox. The coefficient k_1 was chosen to match the value for the loss factor of the full 5-cell cavity which was calculated numerically for a Gaussian bunch distribution. The wake potential shown in Fig. 5 with the blue color is the wake function in Eq. (1) plus the wake function of the fundamental mode integrated over Gaussian bunch distribution. It shows very good agreement with the wake calculated numerically for the actual BNL-3 cavity design. An individual contribution to the wake potential from the high-order modes using Eq. (1) and the fundamental mode is shown in Fig. 6.

For the energy spread calculation from the RF cavities we use the total wake potential, while the fundamental mode contribution is subtracted for the energy loss calculation. The BNL-3 cavity loss factor into the fundamental mode is k_f=0.56 V/pC for 2 mm rms length of a Gaussian bunch, while the loss factor into the high-order modes is k_{HOM}=3.4 V/pC.

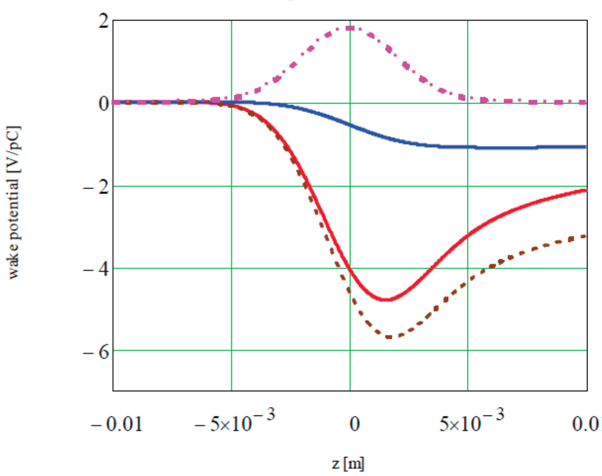

Figure 6: Wake potential for a 5-cell BNL-3 cavity for a Gaussian bunch (magenta) with 2 mm rms length moving to the left: 1) red curve – from HOMs; 2) blue curve – from the fundamental mode; 3) brown dash curve – total.

For the estimates presented, a total contribution from all passes through the linacs was calculated by multiplying wake potential of a single cavity by the total number of cavities and passes. On the other hand, modification of the wake fields along the train of multi-cell cavities was observed in previous studies when the bunch length becomes much shorter than $b^2/(2g)$ [6]. For present parameters of the eRHIC SRF cavity, the bunch length of a few mm corresponds to a regime where we expect to see some but not a significant modification of a single-cell wake. A quantitative comparison with numerical simulations is being planned.

EFFECTS OF THE BUNCH SHAPE

If longitudinal bunch shape is not Gaussian it may affect the above results significantly. Contrary to applications where it is desired to produce rather flat longitudinal bunch distribution, for the eRHIC project, where we need to recover accumulated energy spread, it is preferred to have a rather smooth longitudinal profile to minimize effects from the inductive wakes.

For purely inductive impedance, the wake potential depends on the derivative of the distribution which can lead to stronger effects for the non-smooth distribution. For example, studies of the wall roughness effects showed that not smooth bunch shapes can lead to energy modulations inside the bunch and a significant increase of energy spread [7]. The calculated rms energy spread for the resistive wall is also larger for rectangular longitudinal distribution than for a Gaussian. Therefore, we are presently considering providing an electron distribution which will be close to a Gaussian longitudinally and uniform transversely.

SUMMARY

Here we presented contribution to the energy spread in eRHIC beam transport from the dominant effects of accelerating cavities and resistive wall. A possible contribution from the wall roughness strongly depends on the characteristics of the surface roughness and is presently under study for the extruded aluminum vacuum chambers which are being considered for the eRHIC project. With a preliminary design of the vacuum chambers and components nearly established, contributions to the wake fields from other impedance generating elements will be estimated and presented in the future.

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