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POWER LOSS INDUCED BY WELDING BEADS IN THE HSR BEAM SCREEN OF THE ELECTRON-ION COLLIDER*

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Abstract

In this paper, we present GdfidL-based simulations of resistive wall wake potential and power loss in the beam screen of the Hadron Storage Ring (HSR) of the Electron-Ion Collider (EIC). The resistive wall power loss is calculated from the wake potential computed in the finite-difference 3D electromagnetic code GdfidL. The study includes benchmarking against analytical results and comparison with CST simulations.

INTRODUCTION

The proton beam in the EIC HSR will operate with more than twofold increase in bunch numbers, each with a tenfold shorter bunch length compared to those in RHIC, as shown in Table 1. Consequently, the heating induced by the circulating beam in the vacuum components presents a significant challenge to the cryogenic system. An accurate calculation of the resistive wall heating induced by the beam is crucial for the proper design of the vacuum components.

Table 1: Compare Proton Beam Parameters Between RHIC and HSR (High E_{CM} Mode Operation)

	Number of bunches	R.M.S. bunch length
RHIC	111	60 cm
HSR	290	6 cm

In the past, CST has been used to calculate the resistive wall heating in the beam screen [1,2] by integrating the surface current over the resistive wall of the beam screen. In this work, we use GdfidL [3]to calculate the longitudinal wake potential and the loss factor due to the resistive wall of the screen. The heating power is obtained from the loss factor and compared with what was previously obtained from the CST.

BENCHMARKING GDFIDL WITH ANALYTICAL RESULTS

To ensure that the simulation code, GdfidL, is properly set up for calculating the resistive wall wake potential, we benchmarked its results with the analytical formula. For a beam pipe with circular cross section, the resistive wall wake potential can be calculated from the expression [4]:

$$W_{||} = \frac{\Delta E}{eQ_{bunch}} = \frac{Lc}{2^{3/2}\pi^2 a\sigma_z^{3/2}}\sqrt{\frac{Z_0}{\sigma}}\,G\left(\frac{z}{\sigma_z}\right), \quad (1)$$

where:

$$G(x) = -\int_{-x}^{\infty}\frac{ye^{-\frac{y^2}{2}}dy}{\sqrt{y+x}},$$

a is the radius of the beam pipe, L is the length of the beam pipe, σ_z is the R.M.S. bunch length, σ is the conductivity of the beam pipe and $Z_0 \approx 377\Omega$ is the impedance of the free space. To benchmark GdfidL with the analytical results of eq. (1), we assume that the beam pipe is made of copper with conductivity of $5.8 \times 10^7\ S/m$ and its dimension is as shown in Fig. 1.

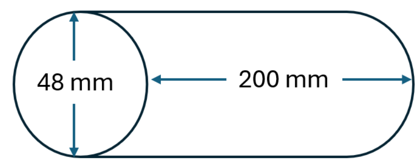

Figure 1: A schematic diagram showing the dimension of cylindrical beam pipe used to benchmark with GdfidL simulation.

As shown in Fig.2, the longitudinal wake potential calculated by GdfidL with the window wake method perfectly agrees with that obtained from the analytical expression of Eq. (1). However, the window wake method is very slow when calculating results with long wake range and fine mesh. Consequently, we use the FDTD method when a fine mesh is needed for the GdfidL simulation.

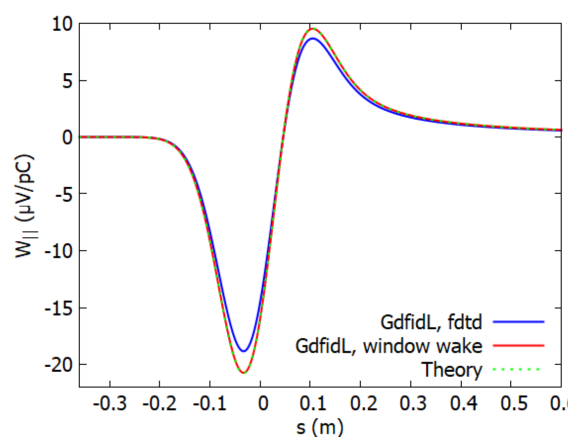

Figure 2: The longitudinal wake potential induced by a proton bunch with the R.M.S. bunch length of 6 cm in a circular copper beam pipe with the dimension shown in Fig. 1. The green dashed curve is obtained from the analytical results, i.e. Eq. (1). The blue solid curve is computed from GdfidL with finite difference time domain (FDTD) method and the red solid curve is computed from the window wake method in GdfidL.

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THE BEAM SCREEN MODEL

The 3D model of the screen used for studying the resistive wall wake potential is shown in Fig. 3. The pumping slots are not included since we are interested in the resistive wall wake potential. The HSR beam screen consists of an amorphous carbon-coated copper-clad stainless-steel pipe. The screen will be fabricated from a single piece with one longitudinal weld to close the screen profile. To avoid any contamination of the copper into the stainless-steel weld, which can jeopardize the mechanical strength of the weld, the copper layer is removed at both sides of the weld joint, exposing a 2 mm wide bead of the stainless steel to the beam. The green strip at the bottom of the model represents the welding bead which has a conductivity of $1.351 \times 10^6\ S/m$. The rest of the beam screen is copper coated and has a conductivity of $5.8 \times 10^7\ S/m$. Three profiles of the welding beads have been considered in the simulation as shown in Fig. 4: no protrusion, 0.2 mm protrusion depth and 0.4 mm of protrusion depth.

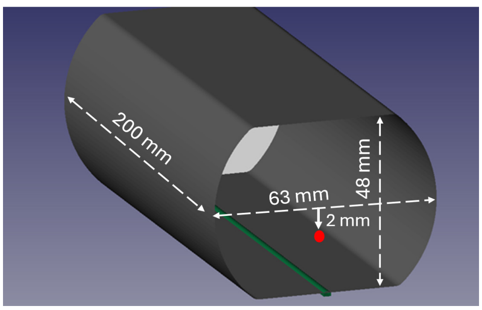

Figure 3: The 3D model used for calculating the resistive wall wake potential for the beam screen in the HSR. The red dot represents the proton beam passing through the beam screen with 2 mm of offset and the green strip represents the steel welding bead of the screen.

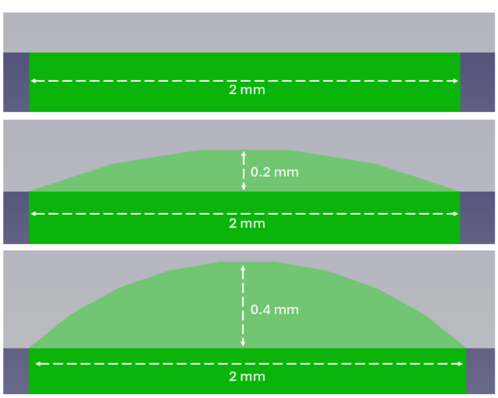

Figure 4: The three profiles of the welding bead considered in the GdfidL simulations.

THE LONGITUDINAL WAKE POTENTIAL AND POWER LOSS

The beam screen as shown in Fig. 3 will be installed in the sections with cryogenic temperature. Since the conductivity of the steel and the copper vary differently with temperature, the contribution from the welding bead and the copper screen must be calculated separately. Figure 5 shows the longitudinal wake potential induced by a proton bunch with the RMS bunch length of 6 cm in the copper beam screen where the welding bead is replaced with a copper strip without protrusion. The proton bunch is assumed to have a vertical offset of 2 mm towards the direction of the welding bead as shown in Fig. 3. The loss factor as calculated from Fig. 5 is 8.676 μV/pC. For the bunch charge of 30.5 nC and 290 bunches in the ring, the power loss rate can be calculated as

$$\frac{P_{loss}}{L_{loss}} = \frac{\kappa_{loss} Q_{bunch} N_{bunch} f_{rev}}{L_{screen}} = 0.915 W/m.$$

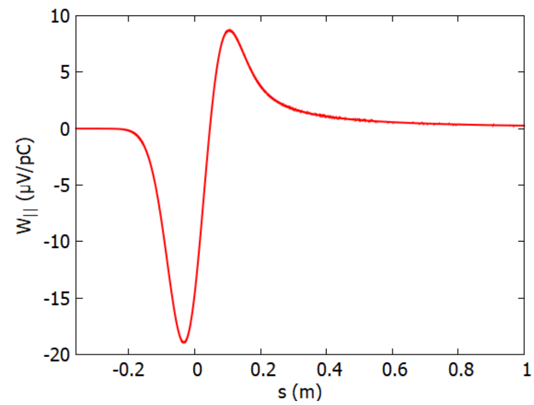

Figure 5: The three profiles of the welding bead considered in the GdfidL simulations.

The power loss rate calculated by CST with the method of integrating the surface current is 0.85 W/m [2], which is about 7% lower than what we obtained from the loss factor as computed by GdfidL. To calculate the contribution from the steel welding bead, we set the welding bead as steel with conductivity of $1.351 \times 10^6\ S/m$ and the rest of the screen is set as perfect electric conductor (PEC) which has no resistivity. Figure 6 shows the longitudinal wake potentials calculated for the welding beads with protrusion of 0 mm (black), 0.2 mm (blue) and 0.4 mm (red).

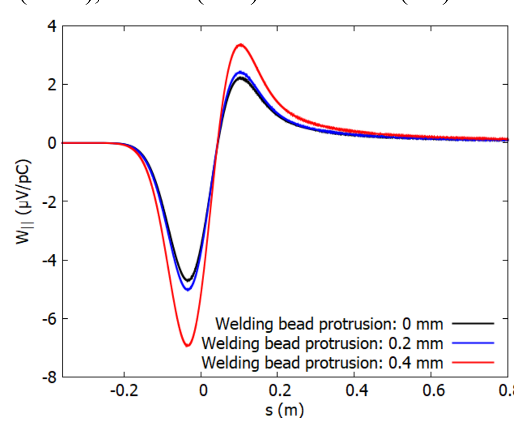

Figure 6: The longitudinal wake potential induced by a proton bunch with the R.M.S. bunch length of 6 cm as it passes through the beam screen with the steel welding bead. The screen is made of PEC and the wake potential is solely due to the welding bead.

As shown in Table 2, the power losses as calculated from the loss factors by GdfidL are smaller than what have been calculated by CST with the method of integrating surface

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current. For the cases of the welding beads having protrusion of 0.2 mm and 0.4 mm, the discrepancies are about 23%. There are two factors that can increase the power loss as the protrusion of the welding bead increases: the increase of the surface area of the welding beads and the increase of the fields around the welding beads.

Table 2: Power Loss Due to the Welding Bead

Protrusion Depth	CST	GdfidL
0 mm	0.250 W/m	0.224 W/m
0.2 mm	0.309 W/m	0.235 W/m
0.4 mm	0.423 W/m	0.325 W/m

The increase of the surface area for a welding bead with protrusion d and width l_{flat} can be calculated from the following expression:

$$\frac{s_{arc}-s_{flat}}{s_{flat}}=\frac{l_{arc}-l_{flat}}{l_{flat}}=\left(\frac{2d}{l_{flat}}+\frac{l_{flat}}{2d}\right)\tan^{-1}\left(\frac{2d}{l_{flat}}\right)$$

where s_{flat} is the surface area for the protrusion depth of 0 mm, s_{arc} is the surface area for the protrusion depth of d and the rest of the variables are defined in Fig. 7.

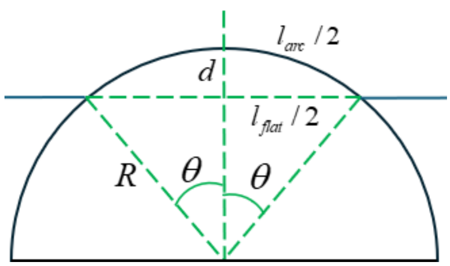

Figure 7: Illustration of the variables used in calculating the surface area of the protruded welding bead.

As shown in Table 3, the relative increases of the power loss are much larger than that of the surface area, indicating that the increases of the field strength with the protrusion depth contributes significantly to the increased power loss.

Table 3: Increases of Surface Area and the Power Loss With the Protrusion Depth of the Welding Bead

Protrusion Depth	CST	GdfidL
0 mm	0.250 W/m	0.224 W/m
0.2 mm	0.309 W/m	0.235 W/m
0.4 mm	0.423 W/m	0.325 W/m

For the previous calculations, we have assumed 2 mm of vertical beam offset. During operation, beam can have different offsets due to injection errors or different operation modes. In Fig. 8 and Fig. 9, we show how the longitudinal wake potential and power loss depend on the vertical beam offset.

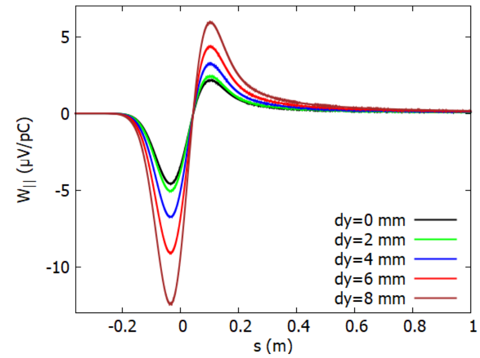

Figure 8: The longitudinal resistive wall wake potential induced by a proton beam with the R.M.S. bunch length of 6 cm and various vertical offsets as it passes through the steel welding bead and the PEC screen.

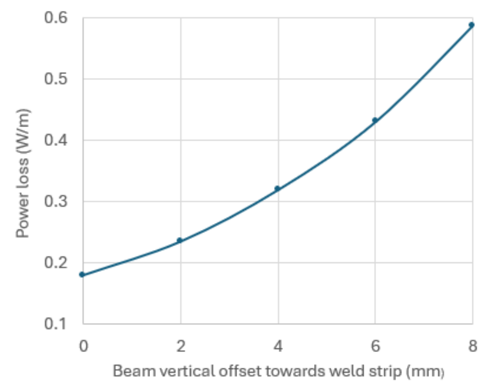

Figure 9: Dependence of the power loss on the vertical beam offset for PEC screen and steel welding bead.

SUMMARY

We have calculated the power loss due to the resistive wall wake potential induced in the HSR beam screen. The studies have been carried out by GdfidL and the power losses are derived from the loss factor associated with the longitudinal wake potential. For the copper beam screen, the power loss as calculated from GdfidL is 7% less than what was previously calculated by CST. However, for the steel welding bead, the power losses calculated from GdfidL are larger than what were previously calculated by CST. For the welding bead with protrusion depth of 0.2 mm and 0.4 mm, the discrepancies between CST and GdfidL are around 23%. To identify the sources of the discrepancy between the results from CST and that from GdfidL, we tried to benchmark the resistive wall wake potential calculation between CST and GdfidL. During the process, we identified some issues with the resistive wall wake potential calculation in CST. For example, for a circular beam pipe made of PEC, the longitudinal wake potential calculated by CST is not zero. The CST team was informed about the issue and hopefully the discrepancies between CST and GdfidL can be reduced after the issue is resolved. We also found that the increase in the power loss with the protrusion depth is mainly due to the increases of the fields around the welding beads, instead of the increased surface area.

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