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SIMULATIONS OF ELECTRON CLOUD LONG RANGE WAKEFIELDS *

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Abstract

A typical approach to electron cloud simulations is to split the problem in two steps: buildup simulations and instability simulations. In the latter step the cloud distribution is usually refreshed after each full interaction with the bunch. This approach does not consider multibunch effects. We present studies of the long range electron cloud wakefields generated in electron clouds after interaction with relativistic proton bunch trains. Several pipe geometries - relevant to CERN accelerators - with and without external magnetic field are considered. Using simple examples we show that the long range wakefields depend significantly on the secondary emission curve as well as on the pipe geometry. Additivity of electron cloud wakefields is studied as well.

INTRODUCTION

Relativistic bunches penetrating electron clouds induce transverse and longitudinal wakes. Transverse wakefields cause instabilities and emittance growth [1]. Whereas longitudinal wakefields are responsible for energy loss and synchronous phase shift [2, 3]. In many cases researchers look for the first unstable bunch in bunch trains. For this purpose one performs scans over electron cloud density. Typically, the electron cloud is assumed to be a very nonlinear object. Thus, most of the beam tracking studies utilize particle-in-cell electron cloud distributions.

In this contribution we investigate the parameters of transverse and longitudnal electron cloud wakefields for CERN-like conditions. We compare the results of 2D and 3D codes. We investigate single-bunch electron cloud wakefields induced by transversely perturbed proton bunches. Moreover, we investigate multi-bunch electron cloud wakefields induced by $k = 0$ bunch mode in bunch trains. The aim is to identify possible regimes where electron cloud representation can be simlified for future beam tracking simulations.

SIMULATION MODEL

For our simulations we utilize two codes: openECLOUD [4] and commercial Vsim [5]. The first code is the electron cloud buildup code from TU-Darmstadt. It utilizes 2D Poisson solver; electron cloud is represented as a 2D slice; the interaction with the beam is purely transverse; stainless steel and copper material models are implemented according to Ref. [6]. For all the simulation we assume rigid, frozen bunches. We take pipe parameters of the super proton synchrotron (SPS) and the large hadron collider (LHC) (set Table 1).

Table 1: Simulation Parameters

Parameter	Value
Bunch length, $\sigma_z[m]$	0.1
Bunch radius, $\sigma_r[m]$	0.01
Bunch spacing, $T[ns]$	25
Bunch population, N_i	10^{11}, 2×10^{11}
Round pipe radius, $R[m]$	0.02
LHC pipe dimensions, $l_x/l_y[m]$	0.044/0.036
SPS MBB dimensions, $l_x/l_y[m]$	0.1218/0.0485
Dipole field, $B[T]$	0.1
Wall materials	copper, stainless steel

SINGLE-BUNCH WAKEFIELDS

In this section we investigate the single-bunch electron cloud wakefields for several bunch parameters. The aim is to indicate the conditions where electron coud wakefields show any linearity.

Figure 1 shows the comparison between the wakefields calculated with openECLOUD and Vsim (3D electromagnetic). The bunch is offcentered as a whole ($k = 0$ head-tail mode), electron cloud fills the cylindrical pipe uniformly. The left plot shows the transverse wakefields obtained directly from the simulations. The right plot shows the longitudinal wakefields. In case of openECLOUD this field is obtained during the data postprocessing. For this purpose we take the derivative of 2D potential with respect to z. One can see that the agreement between the two codes is very good.

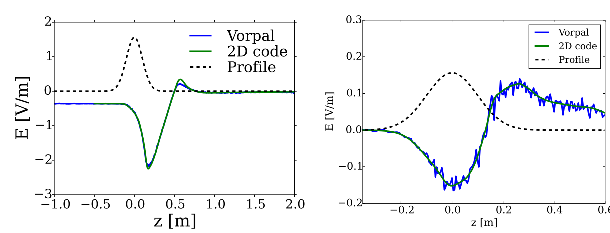

Figure 1: Electron cloud transverse (left) and longitudinal (right) wakefields simulated with Vsim and openECLOUD codes for $N_i = 2 \times 10^{11}$.

Next we analyze the wakefields due to the harmonically excited bunches. All the following simulations are performed using the openECLOUD code. The transverse displacement as a function of longitudinal coordinate is given as follows:

$$\Delta x_k = A_x \sin \frac{2k\pi z}{\lambda_z} \quad (1)$$

, where k is the mode number, A_x is the amplitude, z is the longitudinal coordinate, λ_z is the bucket length. Figure 2 shows the transverse electric fields induced by several

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bunch perturbations. Left side of Fig. 2 depicts the fields for $A_x = 0.2mm$, right side - $A_x = 1mm$. Top curves show simulation results for $k = 4$, $k = 5$ and for the mixed regimes. Bottom curves compare the simulation results for the mixed regime with the sum of single-mode wakefields. One can see that at large perturbation amplitudes the sum overestimates the wakefield amplitude. However, at lower perturbation amplitudes the sum matches the simulation results almost perfectly. Similar results are observed for 5×10^{10} and 2×10^{11} particles per bunch.

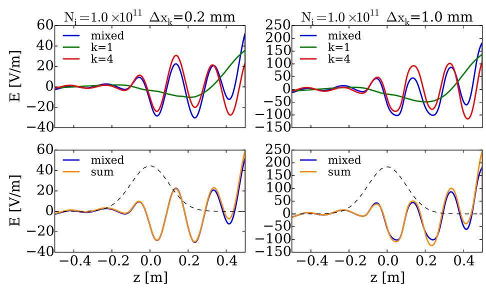

Figure 2: Electron cloud wakefields generated by the perturbed bunches with modes $k = 4$ and $k = 5$. Upper plots show the simulation results for each mode separately and for the mixed modes with the same amplitude. Lower plots compare the sum of the single mode wakefields with the simulations for the mixed mode.

We have seen above that electron cloud wakefields can be additive for smooth realistic bunch perturbations of small amplitudes. In the following we average the electron cloud field over the longitudinal bunch profiles and focus only on $k = 0$ mode. Figure 3 shows the fields on pipe axis and on bunch axis for a bunch offcentered as a whole. One can see that the average field seen by the bunch stays linear for very large bunch displacements. The same linearity can be observed when dipole magnetic field is present (not shown). However, the observed linearity can not be utilized to calculate the tune shift directly - the field along the bunch is not constant (see Fig. 1). Thus, the cloud interaction with the bunch is expected to lead to the detuning.

MULTI-BUNCH WAKEFIELDS

In this section we investigate wakefields induced by a single $k = 0$ perturbed bunch in bunch trains. The first finding is that the strongest long-range fields are induced in presence of magnetic field. Figure 4 shows the electron cloud electric field on pipe axis in presence of dipole magnetic field. The first bunch is offcentered; the following bunches are exactly on the pipe axis. One sees that under the studied conditions the field magnitude grows monotonously with the first bunch offset.

Figure 5 shows the same field as in Fig. 4 but averaged over the bunch profiles. One sees that the field dependence on the offset is rather linear. However, the magnitude of the multi-bunch field is about 15% of the field seen by the first bunch. In case of a stong multipacting (SPS MBB

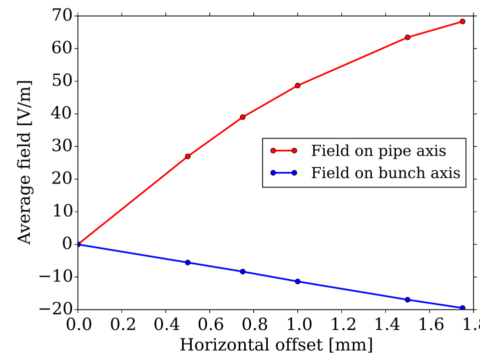

Figure 3: Electron cloud transverse fields in cylindrical geometry averaged over bunch longitudinal profile on bunch axis (blue) and on pipe axis (red). The pipe is cylindrical and $N_i = 10^{11}$.

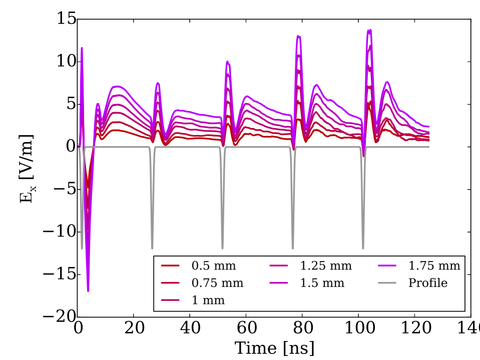

Figure 4: Electron cloud transverse fields on pipe axis excited by $k = 0$ mode of the first bunch in bunch train, in presence of dipole magnetic field. Initial cloud distribution is uniform. The offset is horizontal.

with stainless steel) the multi-bunch field can become significantly larger than the single-bunch field seen by the first bunch (not shown).

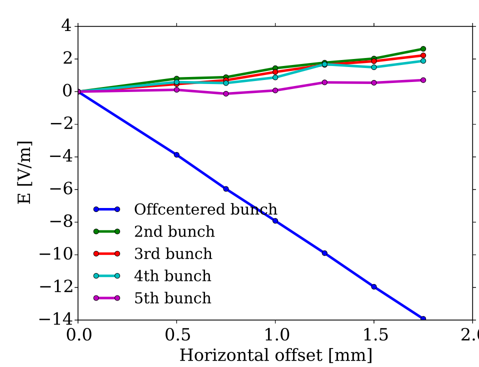

Figure 5: The fields shown in Fig. 4 but averaged over the bunch profiles.

Under the studied conditions the distance to the point were electrons from the wall reach the pipe center [7] is smaller than the bunch spacing. This means that in the

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bunch gap most of electrons interact with the pipe walls and produce secondaries. Thus, the wakefields should depend on the features of secondary emission yield (SEY) (see Fig. 6). Depending on the SEY maximum position, those electrons that are closer to the bunch will produce more or less secondaries than the electrons on the opposite wall.

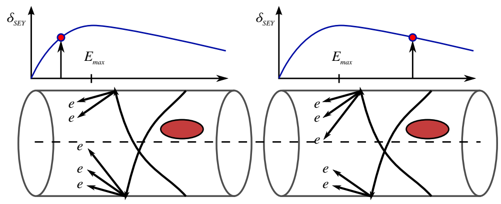

Figure 6: Secondary emission process for different bunch populations/SEY maximum position.

To illustrate this effect we assume LHC dipole geometry and scan over the SEY maximum position. Figure 7 shows the electron cloud fields averaged over the longitudinal bunch profiles for different positions of SEY maximum. All the simulations start with the same uniform cloud distribution. The results indicate that a change of the field sign happens between 300 and 400 eV.

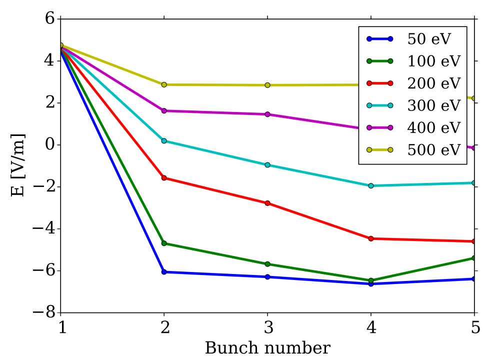

Figure 7: Electron cloud transverse fields on bunch axis averaged over bunch longirudinal profiles for several positions of SEY maximum. The LHC dipole geometry is assumed. The cloud is initially uniform with density $10^9 m^{-1}$.

Up until now we were discussing the case of the only perturbed bunch in a bunch train. Figure 8 shows the electron cloud transverse field seen by the second bunch for several offsets of the first and second bunches. It can be seen that the fields (multi-bunch induced by the first bunch and single-bunch induced by the second bunch) add up linearly.

CONCLUSION AND OUTLOOK

We have studied the transverse and longitudinal electron cloud wakefields by means of openECLOUD and Vsim. We have shown that the code with 2D transverse Poisson solver is sufficient to simulate the wakefields in long pipes under the CERN conditions.

One of the findings of our work is that the restoring force of an electron cloud depends linearly on the transverse

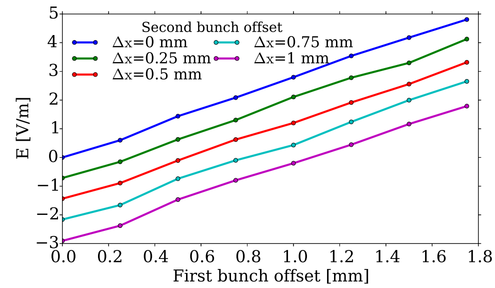

Figure 8: Electron cloud transverse fields averaged over the second bunch profile, excited by $k = 0$ mode of the first and second bunches in bunch train. Initial cloud distribution is uniform.

bunch offset for $k = 0$ head-tail mode. However, the field along the bunch is not constant.

We performed the simulations of electron cloud wakefields induced by smooth bunch perturbations. It was found that for small perturbation amplitudes the electron cloud wakefields can be additive. As a result, an electron cloud wakefield due to complex bunch perturbation can be found as a sum of wakefields due to simple perturbations.

The effect of secondary electron emission on electron cloud wakefields was investigated as well. We focused on the wakefields induced in bunch trains by one $k = 0$ perturbed bunch. We have shown that the multi-bunch electron cloud wakefields are very strong and long-lived in presence of external magnetic field. Our simulations suggest that the multibunch wakefields depend rather linearly on the perturbation amplitude. Moreover, single-bunch and multi-bunch wakefields add up linearly. However, the actual parameters of wakefields depend very strongly on pipe geometry and the SEY, thus each particular case should be studied separately.

In our future studies we plan to investigate whether the instability thresholds predicted with precalculated wakefields match the results for particle-in-cell electron clouds. Moreover, we plan to study the effect of coupling between impedances and electron clouds.

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