SIMULATION OF THE SINGLE BUNCH INSTABILITY DUE TO THE ELECTRON CLOUD EFFECT BY TRACKING WITH A PRE-COMPUTED 2D WAKE MATRIX *

A. Markovik, G. Pöplau, U.van Rienen Universität Rostock, Germany

Abstract

A passage of a positron bunch through an initially homogeneous electron cloud (e-cloud) changes the distribution of the e-cloud in a way that the concentration of electrons in the proximity of the beam axis grows rapidly. The electrons are moving mostly in the transverse plane and are very sensitive on the beam centroid position in that plane. Thus the transverse kick of the e-cloud on the tail particles depends on the centroid position of the head particles of the same bunch. A PIC simulation of the interaction of a positron beam with an e-cloud yields the wake kick from the electrons on the tail particles for a certain offset in the transverse position of the head parts of the bunch. With such a pre-computed 2D wake matrix, for a certain e-cloud density, we investigate the stability of a single bunch by tracking it through the linear optics of the storage ring while at each turn applying the kick from the e-cloud. We examine the positron bunch stability of KEKB-LER for an electron cloud density of $\rho_e = 10^{12}$ electrons $/m^3$.

INTRODUCTION

A number of measurements show that storage rings with positively charged high intensity beams become increasingly vulnerable to the effects of the parasitic electrons in the vacuum chamber as the beam current increases. The parasitic electrons are initially produced by photoemission and ionization. Into the potential of the beam those electrons are accelerated in the transversal plane. After hitting the vacuum chamber walls they produce many secondary electrons. The secondary electrons are then further accelerated by the beam and by repeated hitting at the conducting wall further secondary electrons are released to build the electron cloud (e-cloud). If the storage ring is operated with high positron or proton currents the density of electrons is growing rapidly until a saturation density has been achieved.

The electrons of the cloud have typically an energy of several tens up to a hundred of eV. On the other hand the transversal components of the electrical field of the bunch are very strong (γ times stronger then the field computed in the bunch rest frame) so that the electrons in the potential of the bunch become very mobile in the plane perpendicular to the bunch movement. As a consequence, the e-cloud density in the transversal plane could change very fast. The estimated averaged density of an unperturbed e-cloud in the cross-section of a beam pipe is many orders of magnitude smaller than the positron density in the bunch. However during the beam passage the e-cloud density around and on the beam axes grows rapidly and it is strongly dependent on the parts of the beam that already pass through the certain transverse plane. For instance if the front part of the bunch has an off-set in the transverse plane, with respect to the rear parts of the bunch (Figure 1), it would perturb the e-cloud. The centroid position of the e-cloud moves in the transverse plane so that the e-cloud imposes a dipole kick on the following parts of the the bunch. The dipole kick

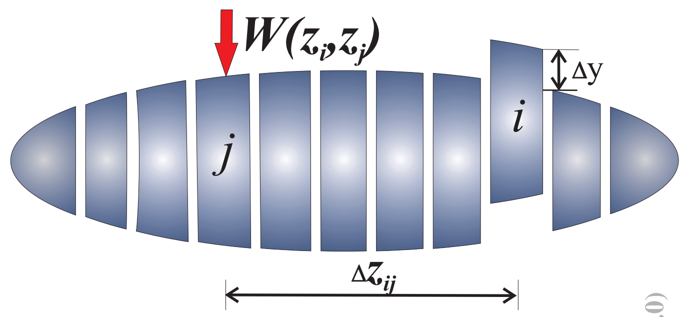

Figure 1: Slicing the 3D bunch in M longitudinal slices and introducing an offset $\triangle y$ in the transversal plane for each slice at the time.

of the e-cloud on the rear parts of the bunch pictures the mechanism of the so called head tail instability, where the position of the head of the bunch induces a kick on the tail of the bunch.

DIPOLE KICK COMPUTATION AND A WAKE MATRIX

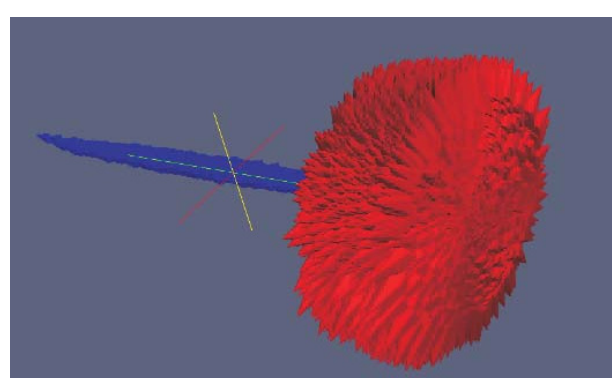

Figure 2: Impulse of the electrons as the whole bunch progressed through.

We compute the dipole kick by a numerical simulation of

* Work supported by DFG under contract number RI 814/20-1

the interaction of a positron bunch and an initially homogeneously distributed e-cloud. The e-cloud fills up a cylindrical beam pipe and its longitudinal dimension we choose to be $1cm$. The 3D bunch is represented by a Gaussian spacial distribution of macro-particles which number is of order 10^6. In longitudinal direction the bunch stretches from $-3\sigma_z$ to $+3\sigma_z$ and for the evaluation of the dipole kick the bunch is sliced in M equally thick slices (dz). If N_p is the total number of particles in the bunch and $\lambda(z) = N_p/\sqrt{2\pi}\sigma_z \exp(-z^2/2\sigma_z^2)$ the Gaussian distribution of them then each slice contains $N_p\lambda(z)dz$ particles. By vertically lifting the slice i at the longitudinal position z_i for a certain $\Delta y \leq \sigma_y$ (as in Figure 1) and simulating the interaction of such a prepared bunch with the e-cloud we receive the average dipole kick $\Delta p_y(j)$ on all the slices positioned at z_j behind the off-set slice ($z_i > z_j$). The induced wake $W_1(z_j, z_i)$ behind the off-set slice i is directly proportional to the computed dipole kick $\Delta p_y(j,i)$ on the slice j. Understanding the e-cloud as a bunch environment which is changing along the bunch passage we follow the idea of K. Ohmi to compute a wake matrix. Since the dipole kick is zero before the off-set slice, the wake matrix is a triangular matrix of dimensions $M \times M$ which holds the computed wakes from the off-set slice backwards. Thus we perform M simulations of the interaction where each of the slices $i = 1, \ldots, M$ has an off-set at a time which is responsible for inducing a dipole kick $\Delta p_y(i,j)$ on the following $j = i, \ldots, M$ slices ($z_i > z_j$). The result of the Particle-In-Cell (PIC) computation by MOEVE PIC Tracking [5] is a dipole kick matrix $\Delta p_y(i,j)$. Finally from the entries of the dipole kick matrix the entries of the wake matrix $W_1(z_j, z_i)$ are given as

$$W_1(z_j, z_i) = \frac{\gamma \Delta p_y(j,i)}{p_b r_e \Delta y_i N_i}, \qquad (1)$$

where p_b is the momentum of the bunch and r_e the classical electron radius. The number of particles in the slice i is N_i, the slice has an offset Δy_i. Such a computed wake

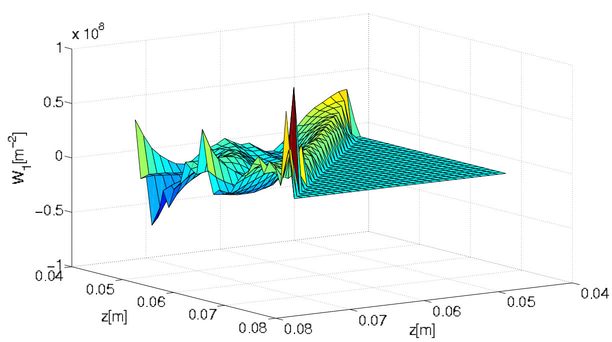

Figure 3: 2D Wake-Matrix for the KEKB-LER for an e-cloud density of $\rho_e = 10^{12}$ electrons $/m^3$.

matrix for a KEKB-LER bunch with the parameters given in the Table 1 and an e-cloud density of 10^{12} electrons$/m^3$ is presented in Figure 3.

Parameter	Symbol	KEKB-LER
Circumference	L	3016 m
Beam energy	E_b	$3,5$ GeV
Population	Nb	$3,3 \cdot 10^{10}$
Charge	Q	$5,28$ nC
Length (rms)	σ_z	6 mm
Transverse	σ_x	420μm
beam size (rms)	σ_y	60μm
Synchrotron tune	ν_s	$0,024$
Betatron tune	$\nu_{x(y)}$	$45,51/43,57$
Damping time	$\tau_{x(y)}$	4000 Turns

Table 1: Bunch parameters of the low energy ring of the KEK B-factory.

SINGLE BUNCH INSTABILITY

In order to estimate the stability of a single bunch we usually need to track it over the time of at least one synchrotron period which lasts over many bunch turns (up to several thousands) in the storage ring. Therefore in the present simulations [2] the bunch interacts with the cloud only on several interaction points (IP's) along the circumference of the ring and elsewhere it undergoes a transformation by the matrices describing the linear beam optics. By following the approach of K. Ohmi, each turn to apply a wake kick on the bunch particles from the pre-computed wake matrix we hope to achieve a relatively fast estimation of the single bunch stability. Hence at each turn with the tracking program PETHS [3] of K. Ohmi the M slices of the bunch receive a kick according to the pre-computed wake matrix by MOEVE PIC Tracking. Thereby the kick at the slice j is a superposition of the kicks induced by all the slices $i = 1, \ldots, j-1$ ahead of the slice j ($z_i > z_j$). The observations in [4] indicate that the transverse kick scales linear with the off-set Δy up until $\Delta y = \sigma_y$. Therefore the kicks induced by slices with smaller off-set $\Delta y < \sigma_y$ are scaled according to the their off-set. The first results of the tracking with the wake matrix are encouraging since we were able to reproduce some results of the measurements. In Figure 4 is ploted the FFT power spectrum of the vertical tune of a KEKB-LER beam collected over 2048 turns. The

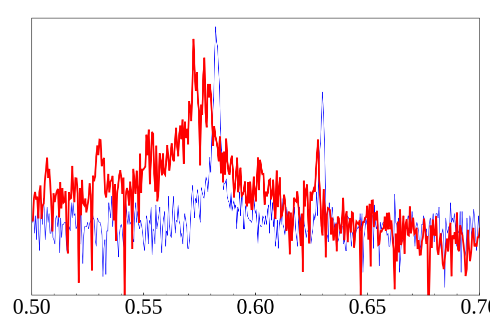

Figure 4: Vertical tune of a single bunch in a train of 100 bunches, measurement (blue) vs. simulation (red) with $M = 30$ slices.

measurement is reported in [1]. The simulation was able to reproduce the observed upper vertical betatron sideband due to electron clouds in the KEKB-LER. For the simulation the bunch was sliced at $M = 30$ slices. However we observed that the results are depending on the size of the wake matrix which equals the number of longitudinal slices M representing the bunch. Figure 5 shows the tune spectrum of the same bunch as in Figure 4 but represented by $M = 22$ (the blue line) and by $M = 40$ (the green line) slices. Both lines show a shift in the betatron tune as well as in the sidebands which are not that distinct as in the simulation with $M = 30$. However all the simulations show

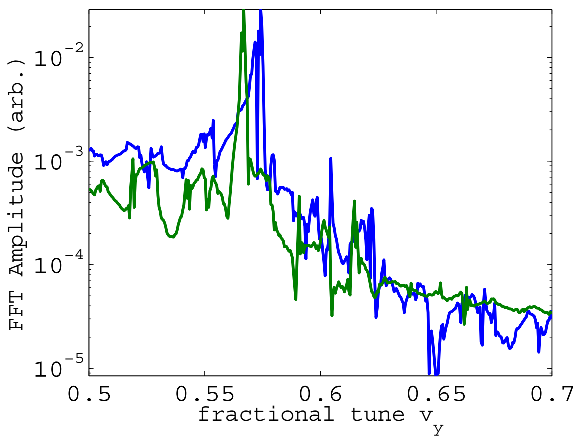

Figure 5: Vertical tune of a single bunch for different number of slices.

the single bunch instability, Figure 6 for $M = 22$ and Figure 7 for $M = 30$. Correspondingly the Figure 8 shows

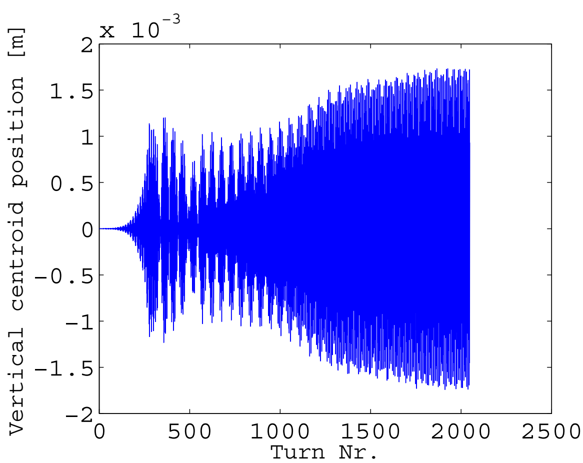

Figure 6: Vertical centroid position of the bunch with $M = 22$ slices.

the blow up of the vertical emittance of the bunch.

ACKNOWLEDGEMENT

Special gratitude to K. Ohmi for his ideas, suggestions and his program.

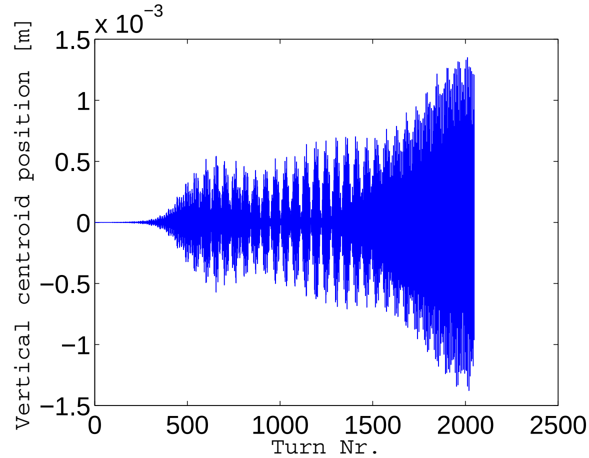

Figure 7: Vertical centroid position of the bunch with $M = 30$ slices.

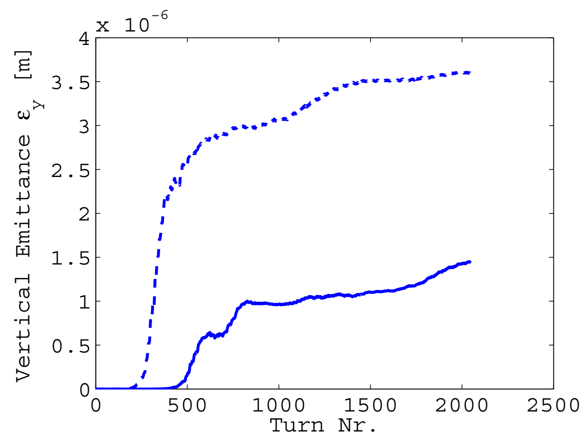

Figure 8: The vertical emittance of the bunch with $M = 30$ (the solid line) and $M = 22$ (the dashed line) slices.

REFERENCES

[1] J. W. Flanagan, K. Ohmi, H. Fukuma, S. Hiramatsu, M. Tobiyama, and E. Perevedentsev. Observation of Vertical Betatron Sideband due to Electron Clouds in the KEKB Low Energy Ring. *Phys. Rev. Lett.*, 94(5):054801, Feb 2005.

[2] E. Benedetto, D. Schulte, F. Zimmermann, and G. Rumolo. Simulation of Transverse Single Bunch Instabilities and Emittance Growth caused by Electron Cloud in LHC and SPS. *Proceedings of ECLOUD'04*, 2004.

[3] K. Ohmi. Particle-in-cell simulation of beam-electron cloud interactions. In *Particle Accelerator Conference, 2001.*, volume 3, pages 1895–1897, 2001.

[4] K. Ohmi, F. Zimmermann, and E. Perevedentsev. Wakefield and fast head-tail instability caused by an electron cloud. *Phys. Rev. E*, 65(1):016502, Dec 2001.

[5] A. Markovik, G. Pöplau, and U. van Rienen. Computation of a Two Variable Wake Field Induced by an Electron Cloud. In *Proceedings of the ICAP09, San Francisco, California, Aug 31- Sept 4.*, 2009.