TRACKING OF A PETRA III POSITRON BUNCH WITH A PRE-COMPUTED WAKE MATRIX DUE TO ELECTRON CLOUDS *

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Abstract

At the synchrotron radiation facility at DESY transversal tune spectra have been observed which are characteristic for an interaction of the positron beam with possible electron clouds in the ring. The filling patterns at which these incoherent tune shifts happen are favorable to the growth of the electron cloud density, i.e. long bunch trains with short intra-bunch distances. Eventually the vertical emittance growth with the originally designed equidistant filling (with 8 or 16 ns bunch spacing) has been avoided by fillings with short bunch trains and longer gaps between them and yet achieving the designed beam current of 100 mA. In this paper we examine the positron bunch stability of PETRA III for certain e-cloud densities and bunch parameters. A PIC simulation of the interaction of the bunch with an e-cloud yields the wake kick on the tail particles for an offset in the transverse centroid position of the head parts. With such a pre-computed wake matrix, we investigate the stability of a single bunch by tracking it through the linear optics of the ring while at each turn applying the kick from the e-cloud. The simulation results are in a good agreement with the measurements.

INTRODUCTION

PETRAIII at DESY is a synchrotron radiation facility running in a top up operation modus with positrons. The machine is characterized (Table 1) by an ultra low emittance and with an emittance ratio of 1% it features very flat bunches. The design beam current of 100 mA was planned to be achieved with fillings of 40 or 960 equally spaced bunches. However, for the filling scheme with 960 bunches with only 8 ns bunch-to-bunch distance a strong vertical emittance growth has been reported for currents about 50 mA [1]. The corresponding measurements of the tune spectra (Figure 1) show sidebands in the vertical tune which suggest incoherent effects. These effects are brought in connection with electron cloud effects on the bunch. Indeed the designed beam current of 100mA has been achieved by filling patterns where the e-cloud can not reach dangerous densities i. e. 60 trains of only 4 bunches with train to train distances of 80ns and bunch to bunch distance of 8ns. The e-cloud build up simulations with ECLOUD 4.0 (reported in [1]) for a train with bunch to bunch spacing of 8 ns and bunch population of $0.5 \cdot 10^{10}$ positrons (SEY δ= 2.5) show that after the first 4 bunches the e-cloud density is still below $5 \cdot 10^{11}$ 1/m^3 which is below the instability threshold computed as in [2]. In 2011 and 2012 further 100 mA runs were performed with trains of 40, 60, 240 and 480 equidistantly spaced bunches with bunch to bunch distance of 192, 128, 32 and 16ns, respectively. Only during the run with 480 bunches a significant emittance growth has been measured. The measurements are very valuable since they give the opportunity to validate the simulations. Eventually the question the instability simulation should answer is at what e-cloud density the instability of a single bunch may occur.

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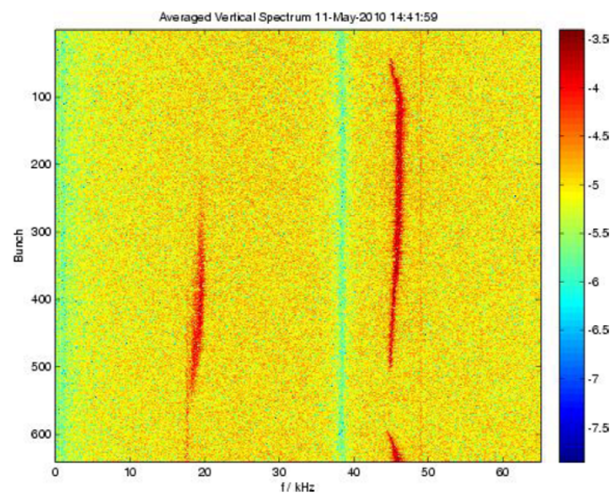

Figure 1: Vertical tune spectra of each of the 640 bunches with 8ns spacing, measured on May 11, 2010 [1]. The total beam current was 62 mA. The red color represents the sidebands and the vertical betatron frequency of 38kHz is green. (Courtesy of R. Wanzenberg.)

SIMULATION

In order to simulate the stability of a single bunch, the bunch particles are tracked through the linear optics of the machine [3]. Thereby the action of the e-cloud on the bunch is approximated by a transverse wake kick which is applied on each turn. The idea of K. Ohmi to slice the 3D bunch and compute a wake function from every longitudinal slice of the bunch backwards, leads to a triangular wake matrix. In order to apply the computed wake matrix for the bunch tracking, properties of the wake field such as time invariance, superposition and linearity are supposed.

The program MOEVE PIC Tracking [4] simulates the interaction of a single bunch with an electron cloud. The cloud is modelled as a uniform distribution of electrons in a beam pipe and is assumed to be generated by the preceding bunches. Since the perturbation of the e-cloud in the transverse plane is due to the transverse displacement

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of the bunch we simulate the interaction by vertically displacing each slice of the bunch by $\Delta y = \sigma_y$. The beam pipe has a small radius of 5 mm and a uniform electron distribution fills a length of 10 mm. The positron bunch is represented by 10^6 macro-particles whereas the cloud, at least for lower densities, is represented by unit charges. In each direction the bunch particles have a Gaussian distribution, longitudinally the bunch spreads from $-3\sigma_z$ to $+3\sigma_z$ and is virtually sliced in $M = 60$ slices. The thickness of the slices in the lab frame corresponds to the time which the electrons on the beam axis need to change their vertical position for one σ_y. The time step used for the interaction simulation is 1 ps. After performing M simulations of the

Table 1: PETRA III Machine Parameters

Parameter	Symbol	PETRA III
Circumference	L	2304 m
Beam energy	E_b	6 GeV
Length (rms)	σ_z	12 mm
Emittance	ϵ_x	1nm
	ϵ_y	0.01nm
Synchrotron tune	ν_s	0.049
Betatron tune	$\nu_{x(y)}$	36.13/30.29
Radiation Damping	horizontal	19.75 ms
	vertical	19.75 ms
	longitudinal	9.84 ms
Momentum compaction factor	α	1.2010^{-4}
RF Frequency	RF	499.564 MHz
Beam Current	I	100 mA
Beam Charge	Q	769 nC
Bunch Charge	Q_b	1.6 nC
Positrons per Bunch	N_b	10^{10}
Mean β function	$\beta_{x/y}$	15 m
Transverse beam size (rms)	σ_x	122.47 μm
	σ_y	17.321 μm

interaction where each of the slices $i = 1, \ldots, M$ has an off-set at a time we receive the change of the vertical momentum $\Delta p_y(i, j)$ of the bunch particles averaged for each trailing slice $j = i + 1, \ldots, M$. Normalizing the dipole kick $\Delta p_y(i, j)$ by the number of particles N_i contained in the displaced slice i and the amount of the displacement Δy_i the entries of the wake matrix $W_1(z_j, z_i)$ write as:

$$W_1(z_j, z_i) = \frac{\gamma \Delta p_y(j, i)}{p_b r_e \Delta y_i N_i} [1/\mathrm{m}^2], \tag{1}$$

where p_b is the momentum of the bunch, γ the Lorentz factor and r_e the classical electron radius. Such a computed wake field can be converted in [V/Cm] by multiplying it with $1/4\pi\varepsilon_0$.

RESULTS

As reported in [5] the run with 480 equidistantly spaced bunches with bunch-to-bunch distance of 16ns show a significant emittance growth. Emittance measurements were made during two days in March 2012 as the beam was used for conditioning of the vacuum chamber (beam scrubbing). Hence we wanted to see if the simulation could reproduce the measurements. The corresponding bunch parameters are given in the second part of Table 1. The starting vertical emittance was taken to be $\epsilon_y = 20$ pm. We computed the wake matrices for the following e-cloud volume densities: $\rho_e = 1 \cdot 10^{11}$ N$_e$/m^3, $\rho_e = 5 \cdot 10^{11}$ N$_e$/m^3 (Figure 2), $\rho_e = 2 \cdot 10^{12}$ N$_e$/m^3 and $\rho_e = 5 \cdot 10^{12}$ N$_e$/m^3 (Figure 3). Plugging the wake matrices and the machine description in K.Ohmi's tracking program PETHS [3] we tracked the bunch for 2048 turns.

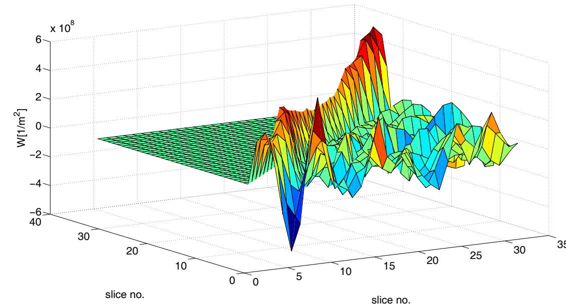

Figure 2: Wake matrix for $\rho_e = 5 \cdot 10^{11}$ N$_e$/m^3.

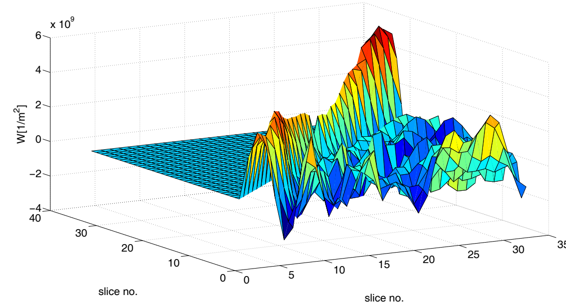

Figure 3: Wake matrix for $\rho_e = 5 \cdot 10^{12}$ N$_e$ /m^3.

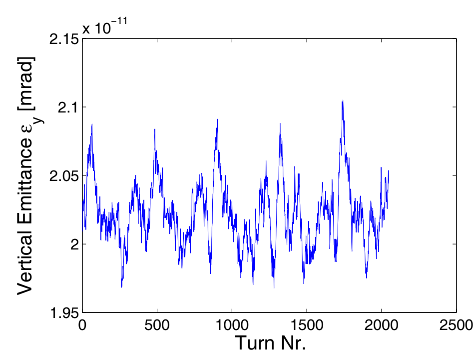

Figure 4: Almost no emittance growth after 2048 turns with $\rho_e = 5 \cdot 10^{11}$ N$_e$/m^3.

The simulation for $\rho_e = 1 \cdot 10^{11}$ N$_e$/m^3 and $\rho_e = 5 \cdot 10^{11}$ N$_e$/m^3, as shown in Figure 4 for $\rho_e = 5 \cdot 10^{11}$ N$_e$/m^3 doesn't reveal any emittance growth over

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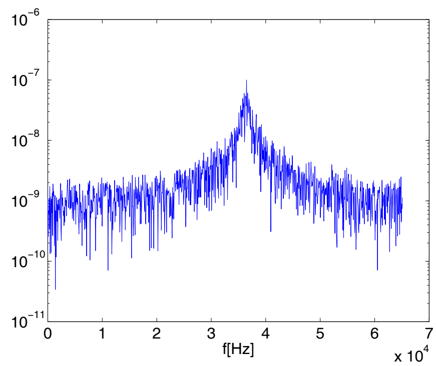

Figure 5: Vertical tune spectra for $\rho_e = 5 \cdot 10^{11}$ N_e/m^3

the 2048 turns. The FFT of the vertical or horizontal centroid position of the bunch during 2048 turns gives the corresponding vertical or horizontal tune spectra. The vertical tune spectra for $\rho_e = 5 \cdot 10^{11}$ N_e/m^3 (Figure 5) shows only the peak at the betatron frequency of 38kHz. However, for higher e-cloud densities ($\rho_e = 2 \cdot 10^{12}$ N_e/m^3 and $\rho_e = 5 \cdot 10^{12}$ N_e/m^3) the vertical tune spectra exhibits side bands (Figure 8) indicating incoherent effects on the bunch. Figure 6 shows the emittance growth for $\rho_e = 2 \cdot 10^{12}$ N_e/m^3 and $\rho_e = 5 \cdot 10^{12}$ N_e/m^3 which is clearly more moderate for the lower e-cloud density.

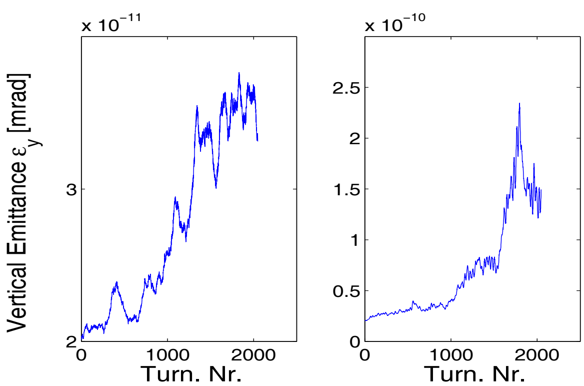

Figure 6: Emittance growth after 2048 turns for $\rho_e = 2 \cdot 10^{12}$ N_e/m^3 (left) and for $\rho_e = 5 \cdot 10^{12}$ N_e/m^3 (right).

CONCLUSION

The tracking simulation using the pre-computed wake matrix for the given bunch was able to predict the instability. As in the measurements the simulation for e-cloud densities above threshold show also sidebands in the betatron tune spectra. The simulated emittance growth seems realistic, even more the emittance from the simulation with $\rho_e = 5 \cdot 10^{12}$ N_e/m^3 seems to match the measured long time emittance (140 pm) from the beam scrubbing run with 480 bunches. Although further validation of the procedure is needed it seems that such a simulation may also be used to numerically estimate the threshold e-cloud density.

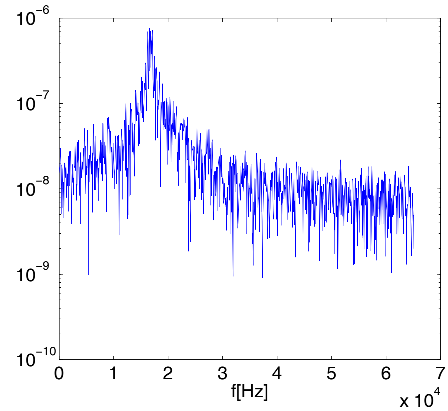

Figure 7: Horizontal tune spectra for $\rho_e = 2 \cdot 10^{12}$ N_e/m^3.

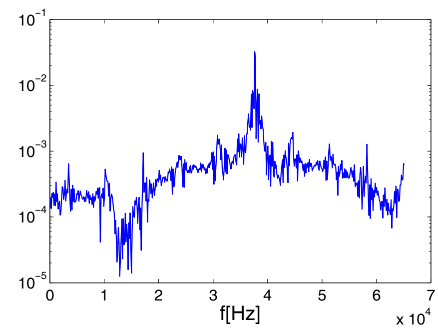

Figure 8: Sidebands in the vertical tune spectra for $\rho_e = 5 \cdot 10^{12}$ N_e/m^3.

ACKNOWLEDGMENT

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