EMITTANCE GROWTH AND TUNE SPECTRA AT PETRA III

R. Wanzenberg*, DESY, Hamburg, Germany

Abstract

At DESY the PETRA ring has been converted into a synchrotron radiation facility, called PETRA III. 20 damping wigglers have been installed to achieve an emittance of 1 nm. The commissioning with beam started in April 2009 and user runs have been started in 2010. The design current is 100 mA and the bunch to bunch distance is 8 ns for one particular filling pattern with 960 bunches. At a current of about 50 mA a strong vertical emittance increase has been observed. During machine studies it was found that the emittance increase depends strongly on the bunch filling pattern. For the user operation a filling scheme has been found which mitigates the increase of the vertical emittance. In August 2010 PETRA III has been operated without damping wigglers for one week. The vertical emittance growth was not significantly smaller without wigglers. Furthermore tune spectra at PETRA III show characteristic lines which have been observed at other storage rings in the connection with electron clouds. Measurements at PETRA III are presented for different bunch filling patterns and with and without wiggler magnets.

INTRODUCTION

At DESY the PETRA ring has been converted into a synchrotron radiation facility, called PETRA III [1]. Originally, PETRA was built in 1976 as an electron and positron collider which was operated from 1978 to 1986 in the collider mode. From 1988 until 2007 PETRA was used as a preaccelerator for the HERA lepton hadron collider ring. Positron and electron currents of about 50 mA were injected at an energy of 7 GeV and accelerated to the HERA injection energy of 12 GeV. During the conversion to a synchrotron radiation facility from 2007 to 2008 one octant of the PETRA ring has been completely redesigned to provide space for 14 undulators. The new experimental hall is shown in Fig. 1. The commissioning with beam started in April 2009 and user runs have been started in 2010 [2]. PETRA III is presently running in a top up operation mode with *positrons* since PETRA III is sharing the same preacelerator chain with the synchrotron source DORIS, which is running with positrons to avoid problems with ionized dust particles.

The new facility aims for a very high brilliance of about 10^{21} photons/s/0.1%BW/mm^2/mrad^2 using a low emittance (1 nm rad) positron beam with an energy of 6 GeV. The very low emittance of 1 nm rad has been achieved with the help of 20 damping wigglers with a length of 4 m each and a peak magnetic field of 1.5 T and a period length of 0.2 m [3].

Figure 1: Aerial view of the new experimental hall of PETRA III which was build from 2007 to 2008.

Beam parameters

A summary of the PETRA III design parameters can be found in Table 1 [1].

Table 1: PETRA III design parameters

Parameter	PETRA III	
Energy /GeV	6	
Circumference /m	2304.0	
Revolution frequency /kHz	130.1	
harmonic number	3840	
RF frequency /MHz	500	
Total current /mA	100	
Bunch Population $N_0/10^{10}$	0.5	12.0
Number of bunches	960	40
Total current /mA	100	100
Bunch separation Δt /ns	8	192
Emittance ϵ_x/nm	1	
ϵ_y/nm	0.01	
Bunch length /mm	12	
Tune Q_x	36.13	
Q_y	30.29	
Q_s	0.049	
Momentum compaction /10^{-3}	1.2	

The design current of 100 mA has been achieved but with a different filling scheme than originally foreseen

* rainer.wanzenberg@desy.de

since a vertical emittance blow-up has been observed for a filling scheme with equidistantly spaced bunches with a bunch to bunch spacing of 8 ns and 16 ns. The emittance blow-up occurred at a total beam current of about 50 mA. Related to the emittance blow-up are additional lines in the tune spectra of the individual bunches. Before the experimental results are discussed the beam current limitation due to coupled bunch instabilities and their cure with powerful multibunch feedback systems are shortly reported in the next subsection.

Beam Instabilities and Feedback Systems

The main reason for beam current limitation due to coupled bunch instabilities is the large parasitic shunt impedance of the seven cell 500 MHz cavities. The measured threshold currents, instability rise times and effective impedances are summarized in Table 2 for PETRA II[1, 4]. PETRA III has almost the same parasitic shunt impedance as PETRA II since presently 12 seven cell 500 MHz cavities are used for PETRA III while in PETRA II 16 cavities of that type were installed. Powerful longitudinal

Table 2: Coupled bunch instabilities

PETRA II	Longt.	Horiz.	Vert.
I_{thres} / mA	7	6	6
$1/\tau$ / Hz	35	50	60
Z_{eff}	3.6 MΩ	45 MΩ/m	54 MΩ/m

and transverse feedback systems with a bandwidth larger than 60 MHz have been installed in PETRA III to damp the bunch oscillations due to coupled bunch instabilities. A schematic layout of the feedback system is shown in Fig. 2, see also Ref. [5]. In a lowest order approximation the beam

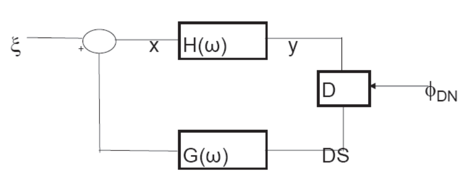

Figure 2: Schematic layout of the PETRA III feedback system [5]: The beam dynamics is described by $H(\omega)$ and the feedback effect by $G(\omega)$ acting on external disturbances of the beam ξ. Φ_{DN} is the noise associated with the feedback detector D.

transfer function $H(\omega) = 1/({\omega_0}^2 - \omega^2)$ may be considered as a harmonic oscillator with a resonant frequency at the tune frequency ω_0 and the effect of feedback is modeled with the function $G(\omega) = i\,\omega\,\Gamma$ with a damping coefficient Γ. The signal from the feedback detector (marked as DS in Fig. 2) is [5]:

$$DS(\omega) = \frac{1}{{\omega_0}^2 - \omega^2 + i\,\omega\,\Gamma}\,\xi + \frac{{\omega_0}^2 - \omega^2}{{\omega_0}^2 - \omega^2 + i\,\omega\,\Gamma}\,\phi_{DN}, \tag{1}$$

where ϕ_{DN} is the detector noise. The detector noise ϕ_{DN} is not transmitted at the tune $\omega = \omega_0$ (see Eqn. 1). Therefore one observes a notch in the tune spectrum at the betatron tune, see Fig. 3. The tune spectra in Fig. 3 were

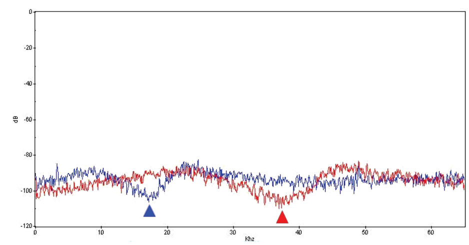

Figure 3: Horizontal (blue line) and vertical (red line) tune spectra of one bunch (#1) in PETRA III. The betatron tunes appear as notches, indicated with arrows in the plot.

recorded for bunch #1 of 40 bunches with a total current of 55 mA, corresponding to a bunch population of $6.6\,10^{10}$ positrons per bunch and a bunch to bunch spacing of 192 ns. This situation may be regarded as a reference where no unusual spectra lines have been observed and the coupled bunch instabilities are well damped with the multibunch feedback system.

MEASUREMENTS

The commissioning of PETRA III [2] with beam started in April 2009 (first stored beam on April 13, 2009). The damping wigglers have been installed on a step by step basis from May 20 to June 25, 2009. After the installation of the damping wigglers the horizontal design emittance of 1 nm has been achieved and the vertical emittance has been $\sim 2\%$ of the horz. emittance. At a diagnostic beam line the horizontal and vertical spot size of the synchrotron light of a bending magnet is analyzed [6]. For some filling schemes a mainly vertical emittance blow-up was observed, correlated with additional lines (sidebands) in the tune spectra. The threshold current of this kind of instability was found to be about 50 mA. Systematic studies of the effect started in May 2010. A filling scheme with 60 short bunch trains with 4 bunches per train was found which avoids any emittance blow-up at the design beam current of 100 mA and is used for user operation.

The main results of the studies with different filling schemes are summarized in this section of this report. The measured tune spectra showed some characteristics which have been observed at other storage rings in connection with electron cloud effects [7, 8, 9]. A unique attribute of the synchrotron light source PETRA III is the large number of damping wigglers (total length 80 m). From Aug. 2 to Aug. 7 PETRA III has been again operated without damping wigglers. It was found that the damping wigglers have no significant influence on the observed emittance growth. In the following subsections the details of the findings are presented.

Studies in May and June 2010

In May 2010 a strong vertical emittance blow-up was observed when a long bunch train of 640 bunches with a bunch-to-bunch distance of 8 ns was stored. The synchrotron light spot at the diagnostic beam line is shown in Fig. 4. This measurement is an average of the beam size of all 640 bunches. There is a strong indication that

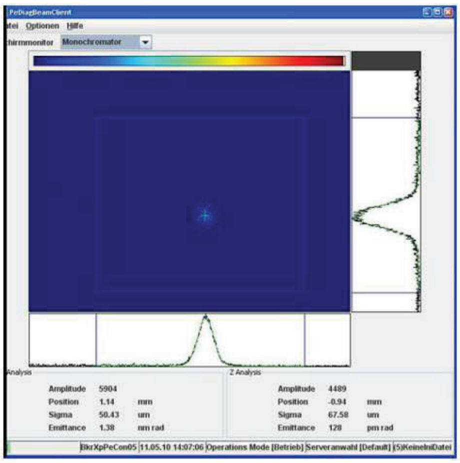

Figure 4: Synchrotron light spot at the diagnostic beam line (May 11, 2010). A significant vertical emittance growth was observed (about a factor 3.5). The total beam current was 65 mA

the large synchrotron light spot results from a single bunch emittance growth and not from a bunch centroid oscillation since the beam life time was growing with beam intensity probably due to a reduced Touschek effect. The emittance growth is correlated with the observation of an extra line (like an upper sideband) in the bunch tune spectrum, which is measured for all individual bunches via the multibunch feedback system. The tune spectrum of bunch #275 is shown in Fig. 5. The notch in the vertical betatron spectrum (red line) indicates the tune (about 39 kHz) and an extra line is clearly seen at a frequency of about 47 kHz. A similar line is observed in the horizontal tune spectrum (blue line) which even seems to be coupled into the vertical plane. The vertical and horizontal tune spectra of a all 640 bunches are shown in Fig. 6 and Fig. 7 using a color code for the spectrum of each bunch. The data are obtained from the multibunch feedback system. The vertical tune is the notch in the tune spectra at about 39 kHz which is not changing along the bunch train, at least within the resolution of the plot.

During the studies in May 2010 a filling scheme with 10 bunch trains of 29 bunches with a bunch to bunch spacing of 8 ns was tried. The filling scheme is shown in Fig. 8. The gap between the bunch trains was larger than 500 ns. Again a vertical emittance growth was observed at a threshold current at about 50 mA. Furthermore additional lines in the tune spectra of the individual bunches were observed, see Fig. 9. The additional line grows in the spectral region

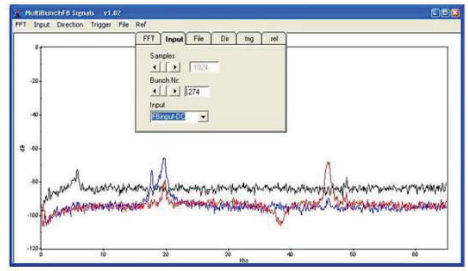

Figure 5: Tune spectrum of bunch #275. The synchrotron tune spectrum (black line) and the betatron tune spectra (horz. blue line, vert. red line) are show.

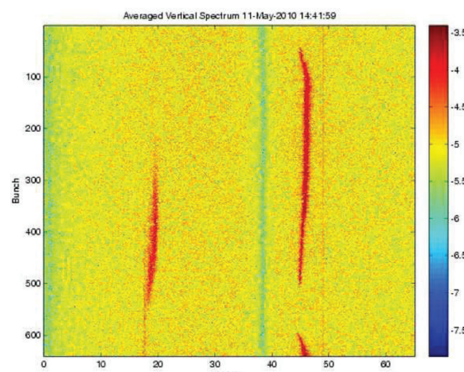

Figure 6: Measured vertical tune spectra of all 640 bunches (May 11, 2010). The total beam current was 62 mA.

of the notch in the spectrum and forms finally a kind of ”upper sideband” of the tune.

Further tests have been done with a bunch train of 200 bunches with a bunch to bunch spacing of 16 ns and a few additional witness bunches behind the bunch train. The goal was to find the minimal distance between a witness bunch and the end of the bunch train at which no addi-

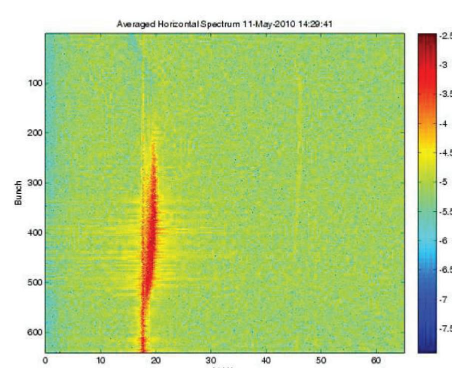

Figure 7: Measured horizontal tune spectra of all 640 bunches (May 11, 2010). The total beam current was 62 mA.

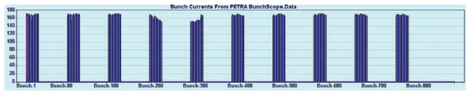

Figure 8: Filling scheme with 10 bunch trains of 29 bunches (May 25, 2010). The bunch to bunch spacing is 8 ns.

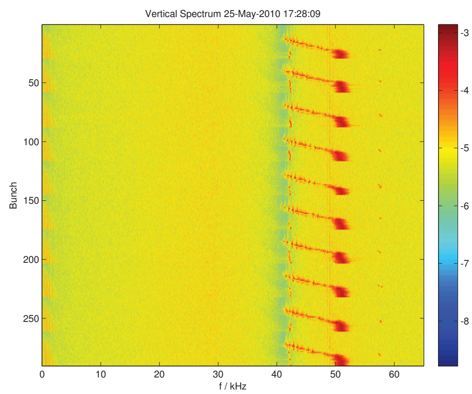

Figure 9: Measured vertical tune spectra of all 10×29 bunches (May 25, 2010). The total beam current was 67 mA.

tional line in the tune spectrum of the witness bunch was observed. It was assumed that the emittance of the witness bunch would not grow since the observed emittance growth was always correlated with additional lines in the tune spectrum. The vertical tune spectra of the 200 bunches are shown in Fig. 10. No additional lines in the spectrum of the witness bunch (not shown in Fig. 10) were observed when the gap between the end of the bunch train and the witness bunch was at least 72 ns or 96 ns (two measurements in May and June 2010).

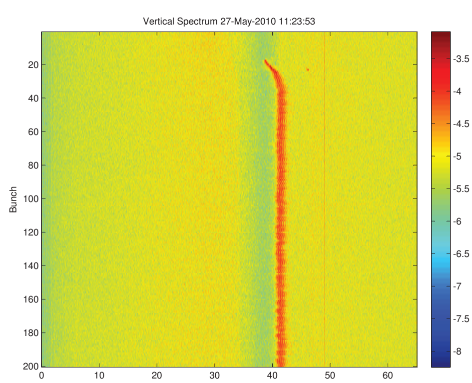

Figure 10: Measured vertical tune spectra of all 200 bunches (May 27, 2010). The total beam current was 47 mA and the bunch to bunch spacing 16 ns.

Based on the measurements with the witness bunches and the observed tune spectra three filling schemes with short bunch trains with only 4 bunches were set-up. The filling patterns are shown in Fig. 11. All schemes use a bunch to bunch distance of 16 ns between the bunches in a train. The number of bunch trains and therefore the gap between the bunch trains differ. The first scheme uses 40 bunch trains with a distance of 144 ns between the bunch trains. The second scheme uses more trains (60) and a distance of 80 ns between the trains. Finally a third scheme with 80 bunch trains and distance of only 48 ns has been used. In May and June 2010 the first scheme was successfully used for user runs with a total bunch current of up-to 70 mA and no vertical emittance blow-up. At the beginning of August a total bunch current of almost 100 mA has been reached with this 60×4 filling scheme. The second filling scheme was regularly used for user runs since September 2010 also without any emittance blow-up and a total bunch current of 100 mA. In May a small emittance growth was observed with this scheme indicating that there was some improvement of the situation. The third scheme always showed a significant emittance blow-up and was never used for user runs. A vertical emittance growth has also been ob-

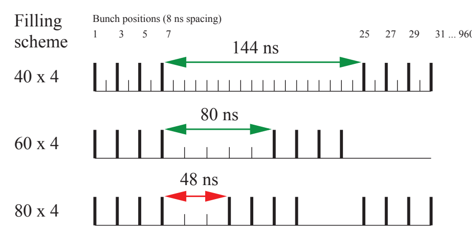

Figure 11: Bunch filling schemes with short bunch trains with 4 bunches and a bunch to bunch spacing of 16 ns.

served when PETRA III was operated with a small number of bunches with a large bunch to bunch spacing. But for these filling schemes it was possible to cure the emittance growth with an increase of the chromaticity from 0.5, the standard setting, to at least a value of 4 and a larger vertical feedback gain. Furthermore a lower sideband instead of a upper sideband was observed in the tune spectra of the bunches. The measured vertical tune spectra of 70 bunches are shown in Fig. 12. PETRA III was operated with one bunch train of 70 bunches with a bunch to bunch spacing of 96 ns between bunches and a gap of 1056 ns at the end of the bunch train. The threshold current for the emittance growth was again about 50 mA when the chromaticity was small (0.5). An increase of the chromaticity helped only for filling schemes with a small number of bunches and a bunch to bunch spacing of at least 96 ns. A larger chromaticity did not help for the filling schemes with a bunch to bunch spacing of 8 ns of 16 ns.

Studies in August 2010 without wigglers

From Aug 2 to Aug 7, 2010 PETRA III was operated with all wigglers moved into the parking position and therefore with an (horz.) emittance of 4.5 nm instead of 1 nm and no magnetic field in the 80 m long wiggler vacuum

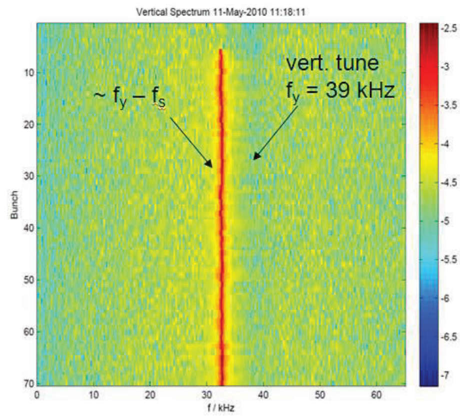

Figure 12: Measured vertical tune spectra of 70 bunches (May 11, 2010). The spacing between the bunches was 96 ns and the total beam current was 55 mA.

chambers. Nevertheless a vertical emittance growth was again observed for several filling schemes at a threshold current of about 50 mA. Additional lines in the tune spectra were also observed.

The vertical tune spectra of a filling scheme with 10 bunch trains of 29 bunches with a bunch to bunch spacing of 8 ns within a train is shown in Fig. 13. The observed spectra are similar to the spectra which have been measured on May 25, see Fig. 9, although some additional lines in the tune spectra were more prominent in May than in the measurements from Aug 5, 2010. The vertical tune spectra of

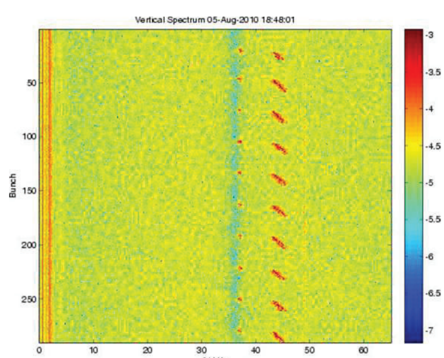

Figure 13: Measured vertical tune spectra of all 10×29 bunches (Aug 5, 2010). The total beam current was 51 mA.

a filling scheme with one bunch train of 200 bunches and a bunch to bunch spacing of 16 ns are shown in Fig. 14. The corresponding measurement with wigglers is shown in Fig. 10. Again several similarities between the spectra from May and from Aug. 5, 2010 are clearly visible. The tune spectra of the first 100 bunches from the two filling schemes of Fig. 13 and Fig. 14 are presented with a different color scheme and in a 3D-plot in Fig. 15 and Fig. 16. In both plots it is visible that an additional line grows in the spectral region of the notch to form finally some type of upper sideband to the tune.

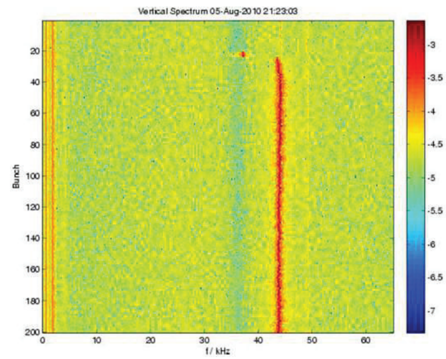

Figure 14: Measured vertical tune spectra of all 200 bunches (Aug 5, 2010). The total beam current was 47 mA and the bunch to bunch spacing 16 ns.

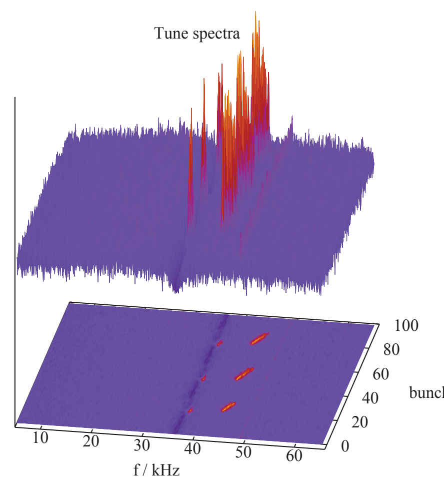

Figure 15: Measured vertical tune spectra of the first 100 bunches of a filling scheme with 10 × 29 bunches (Aug 5, 2010). The total beam current was 51 mA and the bunch to bunch spacing 8 ns.

Studies in August and September 2010

After Aug 7, 2010 all wiggler magnets were placed back into the standard operation position in PETRA III. Further studies have been performed investigating the three filling schemes which are shown in Fig. 11. There was no vertical emittance growth observed for the schemes with 40×4 and 60×4 bunches but there was an emittance growth for the scheme with 80×4 bunches. In Fig. 17 the vertical tune spectra are shown for a filling scheme with 80 trains of 4 bunches. Again some additional lines above the vertical tune notch are visible in the spectra.

In September a similar filling scheme with a gap was used. In Fig. 18 the bunch pattern is shown. In total 40

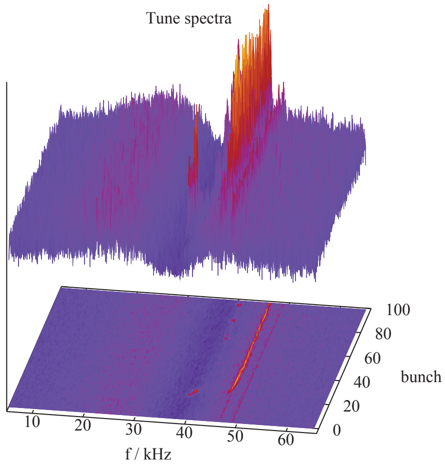

Figure 16: Measured vertical tune spectra of the first 100 bunches of a filling scheme with 200 bunches (Aug 5, 2010). The total beam current was 47 mA and the bunch to bunch spacing 16 ns.

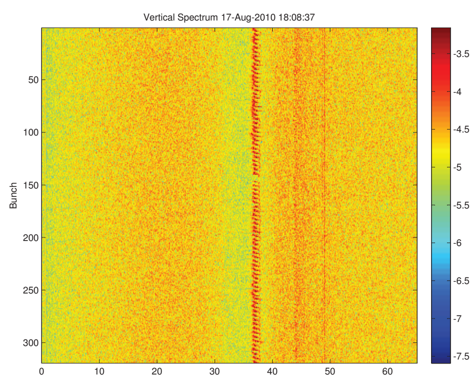

Figure 17: Measured vertical tune spectra of all 80×4 bunches (Aug 17, 2010). The total beam current was 75 mA.

bunch trains of 4 bunches were used with a bunch to bunch spacing of 16 ns. The spacing between the bunch trains was 48 ns. At the end of the bunch trains there was a long gap corresponding to half the circumferences of the PETRA III ring. Also for this filling scheme a vertical emittance

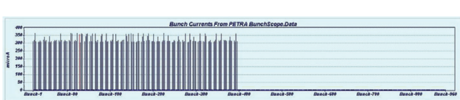

Figure 18: Filling scheme with 40 bunch trains of 4 bunches (Sep 15, 2010). The bunch to bunch spacing was 16 ns and the spacing between the bunch train was 48 ns

growth was observed which was again correlated with additional lines in the tune spectra. The tune spectra are shown in Fig. 19 for all bunches. The spectra of the first bunch trains did not show the additional lines in the tune spectra. But after about 7 bunch trains (or 28 bunches) the additional lines are visible.

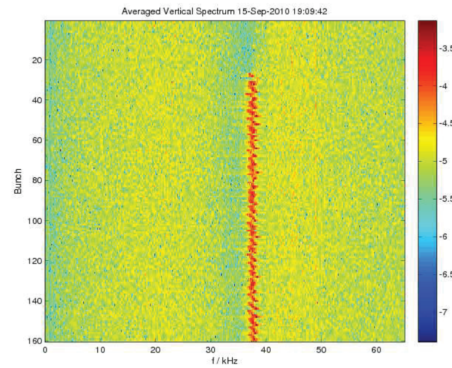

Figure 19: Measured vertical tune spectra of all 40×4 bunches (Sep 15, 2010). The spacing between the short bunch trains was 48 ns The total beam current was 50 mA.

SIMULATIONS

In positron storage rings electrons produced by photoemission and secondary emission form an electron cloud with a charge density which depends on the filling scheme [8, 9]. From the charge density of the electron cloud a broad band impedance model [10] can be obtained which can be compared with the observed threshold currents for the vertical emittance growth at PETRA III and can help to interpret the measurements which are summarized in the previous sections of this report.

Simulation of the build-up of an electron cloud

In 2003 the first simulation for the build-up of electron clouds for PETRA III were done with the computer code ECLOUD 2.3 [11, 12, 13, 14]. More recent simulations of the build-up of an electron cloud in dipole vacuum chambers have been made with the new version 4.0. The vacuum chamber in the dipole magnets is basically an ellipse with a width of 80 mm and a height of 40 mm, see Fig. 20, and is made from aluminum [15, 16]. As an integrated vacuum pump a NEG strip is integrated in an ante chamber, which is placed inside the ring. Synchrotron radiation hits the outer side of the vacuum chamber which is water cooled . For all simulations a primary photo electron emission of 0.065 electrons per meter and positron has been used which is based on a bending radius of about 192 m of the PETRA III dipole magnets (in seven octants without insertion devices) and an assumed effective photo-electron yield of 10 %, see also Ref. [13].

Simulation results for the design parameters of Table 1 (960 bunches) are presented in Fig. 21 and Fig. 22 using $\delta_{max} = 2.5$ for the maximum of the secondary emission

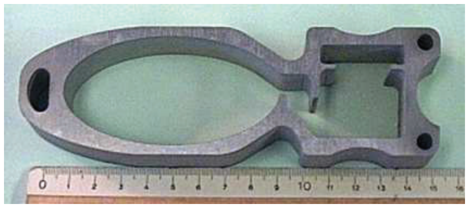

Figure 20: Cut through the vacuum chamber in the PETRA III dipole magnets. The dimension of the ellipse are 80 $\times$ 40 mm.

yield (SEY) at an energy of 300 eV of the primary electron. For these parameters one obtains a center density (ρ_c) of about $1.5 \cdot 10^{12}\,\mathrm{m}^{-3}$ which is a factor 1.8 larger than the average beam charge volume density of

$$\langle \rho_b \rangle = \frac{N}{c\,\Delta t\,A} = 0.83 \cdot 10^{12}\,\mathrm{m}^{-3}, \qquad (2)$$

where N is the positron bunch population, Δt the bunch spacing and A the area of the cross section of the vacuum chamber ($A = \pi \times 20\,\mathrm{mm} \times 40\,\mathrm{mm}$). Simulations with version 2.3 of the ECLOUD code gave a center density of about $1.0 \cdot 10^{12}\,\mathrm{m}^{-3}$ [13], which is closer to the result $\langle \rho_b \rangle \approx \langle \rho_c \rangle$ expected from the condition of neutrality for average charge densities of the cloud and the beam.

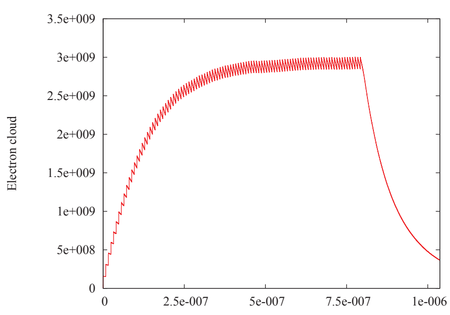

Figure 21: Simulation of electron cloud build-up for a bunch train with a bunch to bunch spacing of 8 ns and bunch population of $0.5 \cdot 10^{10}$ (SEY: $\delta_{max} = 2.5$)

The center density can be translated into a tune shift [17] of

$$\Delta Q = \frac{1}{2}\,\frac{C}{\gamma}\,r_e\,\langle \beta \rangle\,\langle \rho_c \rangle, \qquad (3)$$

where C is the circumference of the ring, γ the relativistic γ-factor, r_e the classical electron radius and $\langle \beta \rangle$ the average betatron function. For PETRA III one obtains for the vertical betatron frequency:

$$\Delta f_y = 0.54\,\mathrm{kHz}\,10^{-12}\,\mathrm{m}^3 \langle \rho_c \rangle. \qquad (4)$$

A center density of $1.5 \cdot 10^{12}\,\mathrm{m}^{-3}$ will therefore give a tune shift of 0.81 kHz.

Further simulations have been done for the filling schemes with 60×4 and 80×4 bunches from Fig. 11

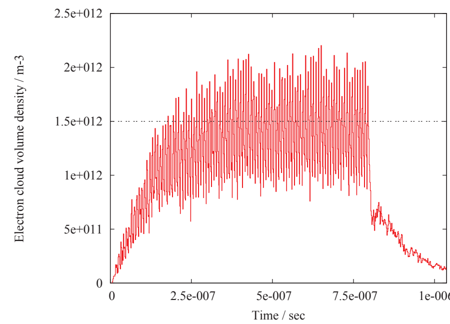

Figure 22: Center density of the electron cloud build-up for a bunch train with a bunch to bunch spacing of 8 ns and bunch population of $0.5 \cdot 10^{10}$ (SEY: $\delta_{max} = 2.5$)

since for the 60×4 filling scheme no emittance blow-up was observed while the bunches from the 80×4 filling scheme clearly showed an increase of the emittance. The results for these filling schemes are presented in Fig. 23 and Fig. 24. In both cases a total bunch current of 50 mA have been assumed resulting in bunch population of $1.0 \cdot 10^{10}$ and $0.75 \cdot 10^{10}$ positrons per bunch. This total current was just the threshold current for the observed emittance growth for the 80×4 filling scheme. The bunch to bunch spacing between the four bunches of one train was 16 ns while the distance between the bunch trains was 80 ns and 48 ns as shown in Fig. 11. The simulation did not show any significant difference between the center density for the two schemes which could explain the observed results. In both cases the center density was about $1.0 \cdot 10^{12}\,\mathrm{m}^{-3}$.

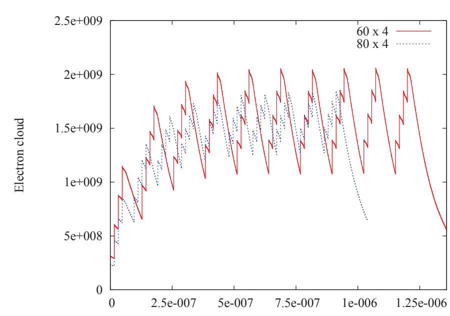

Figure 23: Simulation of electron cloud build-up for a 60x4 and 80x4 bunch filling and bunch population of $1.0 \cdot 10^{10}$ and $0.75 \cdot 10^{10}$ (SEY: $\delta_{max} = 2.5$)

Electron cloud threshold density

The simulated electron cloud densities can be compared with the threshold density $\rho_{e,th}$ for an instability which are obtained from an approach by K. Ohmi [18] which is based on a combination of a broad band resonator model for the impedance [10] and a coasting beam model for the insta-

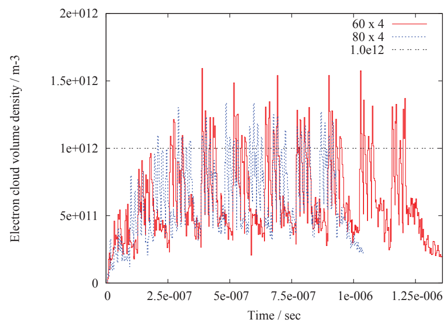

Figure 24: Center density of the electron cloud build-up for a 60x4 and 80x4 bunch filling and bunch population of $1.0 \cdot 10^{10}$ and $0.75 \cdot 10^{10}$ (SEY: $\delta_{max} = 2.5$)

bility:

$$\rho_{e,th} = \frac{2\,\gamma\,Q_s\,\omega_{e,y}\,\sigma_z/c}{K\,Q_{res}\,\sqrt{3}\,r_e\,\langle\beta_y\rangle\,C}, \tag{5}$$

where Q_s is the synchrotron tune, $Q_{res} \approx 5$ is the Q-value of the broad band impedance model, K is a factor to take into account the pinch effect and $\omega_{e,y}$ is the oscillation frequency of the electrons in the bunch potential. All other parameters have the same meaning as in Eqn. 3. For the design parameters of PETRA III (960 bunch operation mode) one obtains the following threshold densities (see Table 3):

Table 3: PETRA III threshold density

PETRA III	$K = 1$	$K = \omega_{e,y}\,\sigma_z/c$
$\rho_{e,th}$	$8.9 \cdot 10^{12}\,\mathrm{m}^{-3}$	$1.4 \cdot 10^{12}\,\mathrm{m}^{-3}$

Table 3 summarizes the threshold density for two values of the parameter K. According to Ref. [18] a parameter K about $\omega_{e,y}\,\sigma_z/c$ is usually a good approximation. For $K = \omega_{e,y}\,\sigma_z/c = 6.4$ the threshold density of $1.4 \cdot 10^{12}\,\mathrm{m}^{-3}$ is just a bit smaller than the electron cloud density obtained from the simulations with version 4.0 of the computer code ECLOUD (see Fig. 22). This indicates that the observed emittance growth for the filling scheme with 640 bunches, observed in May 2010, is due to an instability driven by an electron cloud. But from simulations for the filling schemes with 60×4 and 80×4 bunches one obtains an electron cloud density which is below the threshold density while the measurements show an emittance growth for the filling scheme with 80×4 bunches.

CONCLUSION

At PETRA III a strong vertical emittance increase has been observed which depends strongly on the bunch filling pattern. The measured tune spectra showed some characteristics (see Fig. 6 and Fig. 7) which have been observed at other storage rings in connection with electron cloud effects. In seven octants of PETRA III the vacuum chambers in the dipole magnets are made from aluminum which has initially ('as received') a maximum secondary emission yield of about 3 which goes done to 1.5 after intense scrubbing of the surface [19]. The simulated electron density for the PETRA III design parameters in the 960 bunch operation mode is just above the threshold density according the model from Ref. [18] when the results from version 4.0 of the ECLOUD code and a K equal to $\omega_{e,y}\,\sigma_z/c$ are used. These facts indicate that the observed vertical emittance increase in PETRA III could be due to an electron cloud driven instability.

But there are several observations which do not fit well with the results obtained from simulations of electron clouds. One would expect that the frequency of the notch in the tune spectra would depend on the bunch number along the bunch train according to Eqn. 3 for the tune shift. This was not observed, but an additional line in the spectra was found to grow in the region of the notch, finally forming a type of upper sideband. The location of the line saturates after about 25 bunches (see Fig.9) while the electron cloud density saturates after about 50 bunches (see Fig.21). No emittance growth has been observed for the filling schemes with 60×4 bunches while there was a significant emittance growth for the filling scheme with 80×4 bunches. These observations could not be explained with the simulation results for these filling schemes. It is very unlikely that the emittance growth for the filling scheme with 70 bunches is related to electron cloud effects since the bunch spacing is 96 ns. It is not yet understood whether and how the multibunch feedback system is also acting on the single bunch in a way which influences the single bunch emittance.

For the user operation with design current of 100 mA a filling scheme with 60×4 bunches was found which avoids any emittance growth. Nevertheless further studies using TE-wave transmission measurements, using the techniques from [20] are planned to obtain a better understanding of the observations.

ACKNOWLEDGMENTS

I would like to thank J. Crittenden for discussions and his electron cloud simulations for PETRA III. Thanks go also to R. Cimino for the measurement of the secondary electron yield of Aluminum samples from the PETRA III vacuum chamber. Further thanks go to my colleagues from DESY: K. Balewski, M. Bieler, J. Keil, A. Kling, G.K. Sahoo who provided valuable data and facts for my talk and the report. Last but not least I would like to thank M. Lomperski for carefully reading the manuscript.

REFERENCES

[1] Editors: K. Balewski, W. Brefeld, W. Decking, H. Franz, R. Röhlsberger, E. Weckert, "PETRA III: A low Emittance Synchrotron Radiation Source", DESY 2004-035, February 2004.

[2] K. Balewski, "Commissioning of Petra III," Proceedings of

1st International Particle Accelerator Conference: IPAC'10, Kyoto, Japan, 23-28 May 2010.

[3] M. Tischer *et al.*, "Damping Wigglers at the PETRA III Light Source," Proceedings of 11th European Particle Accelerator Conference (EPAC 08), Magazzini del Cotone, Genoa, Italy, 23-27 Jun 2008.

[4] K. Balewski and R. Wanzenberg, "Beam current limitations in the synchrotron light source PETRA III," Proceedings of 9th European Particle Accelerator Conference (EPAC 2004), Lucerne, Switzerland, 5-9 Jul 2004.

[5] K. Balewski *et al.*, "Commissioning Results of Beam Diagnostics for the PETRA III Light Source", Proceedings DIPAC'09, Basel, Switzerland, May 2009

[6] G. Kube *et al.*, "Petra III Diagnostics Beamline for Emittance Measurements," Proceedings of 1st International Particle Accelerator Conference: IPAC'10, Kyoto, Japan, 23-28 May 2010.

[7] K. Cornelis, "The electron cloud instability in the SPS," Mini Workshop on Electron Cloud Simulations for Proton and Positron Beams (ECLOUD'02), Geneva, Switzerland, 15-18 Apr 2002.

[8] K. Ohmi, "Beam and photoelectron interactions in positron storage rings", Phys. Rev. Lett. **75** (1995) 1526.

[9] F. Zimmermann, "The electron cloud instability: Summary of measurements and understanding," Proceedings of IEEE Particle Accelerator Conference (PAC 2001), Chicago, Illinois, 18-22 Jun 2001, pp 666-670.

[10] K. Ohmi, F. Zimmermann, E. Perevedentsev, "Wake-Field And Fast Head - Tail Instability Caused By An Electron Cloud", Phys. Rev. E **65** (2002) 016502.

[11] G. Rumolo and F. Zimmermann, "Electron-cloud simulations: Buildup and related effects," Mini Workshop on Electron Cloud Simulations for Proton and Positron Beams (ECLOUD'02), Geneva, Switzerland, 15-18 Apr 2002.

[12] G. Rumolo and F. Zimmermann, "Practical User Guide for ECLOUD", CERN-SL-Note-2002-016, CERN, Geneva, Switzerland, 2002.

[13] R. Wanzenberg, "Prediction of Electron Cloud Effects in the Synchrotron Light Source PETRA III", Internal Report, DESY M 03-02, Dec. 2003.

[14] R. Wanzenberg, "Prediction of Electron Cloud Effects in the Synchrotron Light Source PETRA III", Proceedings ECLOUD'04, Napa, April 2004, CERN-2005-001, p. 169 (2005).

[15] M. Seidel, R. Böspflug, J. Boster, W. Giesske, U. Naujoks and M. Schwartz, "The vacuum system for PETRA III," Proceedings of Particle Accelerator Conference (PAC 05), Knoxville, Tennessee, 16-20 May 2005, pp 2473.

[16] R. Böspflug *et al.*, "Vacuum system design of the third generation synchrotron radiation source PETRA III," J. Phys.: Conf. Ser. **100** 092012, 2008

[17] K. Ohmi, S. Heifets and F. Zimmermann, "Study of coherent tune shift caused by electron cloud in positron storage rings," Proceedings of 2nd Asian Particle Accelerator Conference (APAC '01), Beijing, China, 17-21 Sep 2001.

[18] K. Ohmi, "Electron cloud effect in damping rings of linear colliders," 31st ICFA Beam Dynamics Workshop on Electron Cloud Effects (ECLOUD04), Napa, California, 19-23 Apr 2004

[19] R. Cimino, "private communication", LNF-INFN, Frascati, Italy, 2010

[20] S. De Santis, J. M. Byrd, F. Caspers, A. Krasnykh, T. Kroyer, M. T. F. Pivi and K. G. Sonnad, "Measurement of Electron Clouds in Large Accelerators by Microwave Dispersion," Phys. Rev. Lett. **100** (2008) 094801.