OBSERVATIONS OF ELECTRON CLOUD PHENOMENA AT PETRA III

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Abstract

PETRA III is a third generation synchrotron radiation facility at DESY, which is presently operated with positron beams. Regular user operation started in mid 2010 after a commissioning phase which began in April 2009. The design current of 100 mA has been achieved but with different number of bunches and bunch to bunch distances than originally foreseen since a strong vertical emittance growth was observed for the design bunch filling pattern with 960 bunches. During machine studies different bunch filling patterns have been tested. In 2012 two scrubbing runs with 480 bunches and a bunch to bunch spacing of 16 ns have been done. The recent measurements indicate that the scrubbing runs have mitigated the emittance growth. Furthermore conditioning effects have been observed during the user runs in 2011. The results from the measured emittances and tune spectra are reported.

INTRODUCTION

PETRA III [1] is a third generation synchrotron radiation facility at DESY. The PETRA ring was built in 1976 as an electron and positron collider and used as a preaccelerator for the HERA lepton hadron collider ring from 1988 until 2007. During the conversion to a synchrotron radiation facility from 2007 to 2009 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 preaccelerator chain with the synchrotron source DORIS, which is running with positrons to avoid problems with ionized dust particles.

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]. 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].

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	100
Bunch Population $N_0/10^{10}$	0.5	12.0
Number of bunches	960	40
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 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. First observations of the instability are reported in [4]. There were indications already in 2009 that the vertical emittance increase is related to electron cloud effects [5, 6]. In 2010 filling schemes with short trains of 4 bunches and different spacings between the bunch trains (144 ns and 80 ns) have been used, see Fig. 11 in [4]. During the user runs in 2011 and 2012 three different filling scheme have been mainly used with a bunch spacing of 32 ns, 128 ns and 192 ns, see Table 2 and Fig. 2. The filling schemes with 60 and 40 bunches are used for time resolved measurements. No emittance growth related to electron cloud effects is observed for these two schemes.

Instability threshold

The threshold density $\rho_{e,th}$ for the onset of electron cloud effects can be estimated from an approach by

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Table 2: PETRA III parameters 2011/2012

Parameter	User runs		
Total current /mA	100	100	80
Bunch Population $N_0/10^{10}$	2.0	8.9	9.6
Number of bunches	240	60	40
Bunch separation Δt /ns	32	128	192

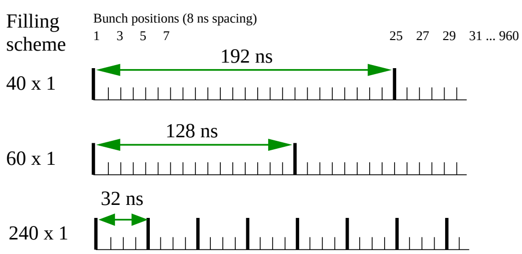

Figure 2: Filling schemes for the user runs in 2012. The smallest bunch to bunch spacing is 32 ns.

K. Ohmi [7] which is based on a combination of a broad band resonator model for the impedance [8] and a coasting beam model for the instability:

$$\rho_{e,th} = \frac{2\,\gamma\, Q_s\, \omega_{e,y}\, \sigma_z/c}{K\, Q_{res}\, \sqrt{3}\, r_e\, \langle \beta_y \rangle\, C}, \tag{1}$$

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. 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 and σ_z is the bunch length. Assuming that $K \approx \omega_{e,y}\, \sigma_z/c$ one obtains the following threshold density (see Table 3):

Table 3: PETRA III threshold density

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

Vacuum system

The vacuum chamber, which is installed in the PETRA III dipole magnets, is shown in Fig. 3 [9, 10]. An integrated vacuum pump with NEG strip is integrated in an ante chamber, which is placed on the inner side of the PETRA ring. Synchrotron radiation hits the outer side of the vacuum chamber which is water cooled. The chamber is made from aluminum and had initially (as received) a maximum secondary emission yield (SEY) of $\delta_{\max} = 2.7$ [11]. After an electron dose of $1.2 \cdot 10^{-2}\ \mathrm{C/mm^2}$ the maximum

Figure 3: Vacuum chamber of the PETRA III dipole magnet. The dimension of the ellipse are 80 $\times$ 40 mm.

SEY is reduced to 1.5 to 1.8 depending on the vacuum conditions in the laboratory measurements [11]. In 2012 the measured average vacuum pressure in PETRA III without beam is $5.0 \cdot 10^{-10}$ mb and about $1.5 \cdot 10^{-8}$ mb with beam (100 mA).

MEASUREMENTS

The commissioning of PETRA III [2] with beam started in April 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. The vertical emittance was about 20 pm corresponding to an emittance coupling of about 2%. But for some filling schemes with many bunches a mainly vertical emittance blow-up was observed, correlated with additional lines (sidebands) in the tune spectra. For the user runs in Aug. 2010 short trains of 4 bunches and different spacings between the bunch trains have been used to avoid an emittance growth [4]. In 2011 it was possible to use a filling scheme with 240 equally spaced bunches (bunch spacing of 32 ns), see Fig. 2, which clearly indicates a conditioning effect. At the end of the user runs in 2011 the integrated beam current was nearly 1000 Ah. In March 2012 two dedicated scrubbing runs were performed. After the scrubbing runs the emittance has been measured for different bunch filling schemes. The main results of the studies are summarized in this section of this report.

Emittance diagnostic

At PETRA III a special diagnostic beam line is used to measure the horizontal and vertical spot size of the synchrotron light of a bending magnet [12]. From the spot size the emittance is calculated. A measurement from a user run with 240 bunches and a total bunch current of 100 mA is shown in Fig. 4. The beam size corresponds to an average which includes all 240 bunches. From the spot size a horizontal emittance of 1.18 nm was calculated. Due to an aberration in the optical beamline it is not possible to measure a vertical emittance smaller than 35 pm. For the example in Fig. 4 the calculated and displayed vertical emittance was 37 pm.

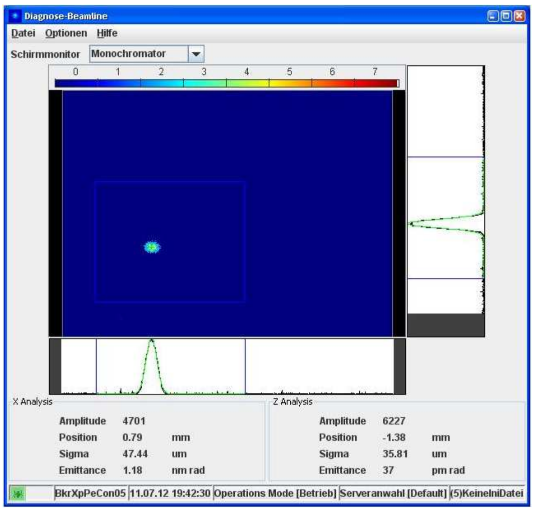

Figure 4: Measured photon spot size from the diagnostic beam line of PETRA III. From the rms spot size a horizontal emittance of 1.18 nm is calculated. The total beam current of 100 mA was stored in 240 bunches (32 ns bunch spacing).

Since 2012 an interferometric vertical beam size measurement [13, 14, 15, 16] is used to obtain a more accurate measurement of the vertical emittance. The principle of the measurement is shown in Fig. 5. Synchrotron light from a bending magnet is sent through a double slit and generates an interference pattern. The beam size is calculated from the visibility of the interferogram, which indicates the degree of spatial coherence of the photons. A measurement of the vertical beam size at PETRA III is shown in Fig. 6. From the beam size a vertical emittance of about 5 pm was calculated for this measurement (March 8, 2012), which corresponds to an emittance coupling of 0.5 %.

Scrubbing runs

In 2012 two dedicated scrubbing runs with a total time period of four days (two weekends, March 3-4 and March 10-11, 2012) have been performed with a filling scheme of 480 equally spaced bunches and a total beam current of 100 mA, see Fig. 7. The integrated beam was about 10 Ah.

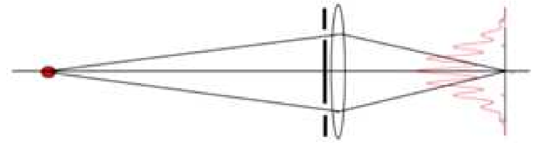

Figure 5: Principle of the interferometric vertical beam size measurement.

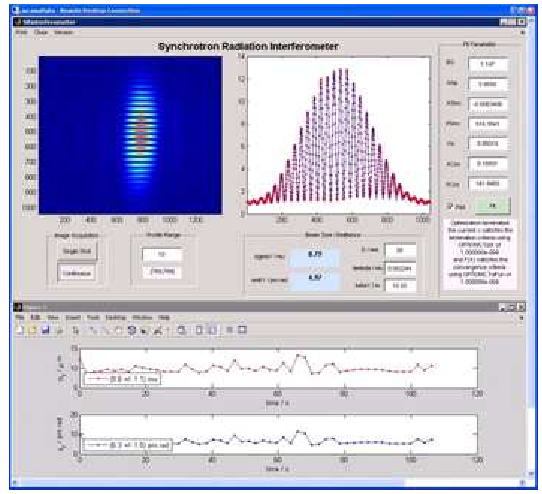

Figure 6: Measured interference pattern to determine the vertical emittance. From the beam size a vertical emittance of about 5 pm was calculated (March 8, 2012).

The photoelectron dose d_{ch} on the dipole chamber wall can be estimated from the mean number of emitted photons per length:

$$\frac{dN_\gamma}{dz} = \frac{5}{2\sqrt{3}} \, \frac{1}{137} \, \frac{E}{m_0\, c^2} \, \frac{1}{\rho} = 0.065 \, \frac{1}{\mathrm{m}}, \qquad (2)$$

and integrated beam current $\int I \, dt$:

$$d_{ch} = Y \, \frac{dN_\gamma}{dz} \, \frac{1}{C_{ch}} \int I \, dt = 1.2 \, 10^{-2} \, \mathrm{C/mm^2}, \qquad (3)$$

where $\rho \approx 190\,\mathrm{m}$ is the bending radius of the dipole magnet in the arc, $Y \approx 0.1$ is the primary photoelectron emission yield and $C_{ch} = 194\mathrm{mm}$ is the inner circumference of the vacuum chamber (Fig. 3). The estimated photoelectron dose during the scrubbing runs is similar to the dose applied to the Al samples in the laboratory [11]. In the laboratory the measured maximum secondary emission yield δ_{max} was reduced to about 1.8 for vacuum conditions similar to those in the PETRA III vacuum system.

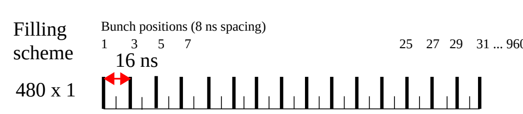

Figure 7: Bunch filling patterns for the scrubbing runs with 480 bunches and a bunch to bunch distance of 16 ns.

During the the scrubbing runs the beam emittance was monitored at the diagnostic beam line. In Fig. 8 a screen shot of the archive data viewer is shown. The horizontal scale covers a time range of 100 h from March 9, $00:00$ h to March 13, $04:00$ h. On the vertical scale the beam current (green line), the number of bunches (blue line), the vertical emittance (red line) and the horizontal emittance (black line) are shown in normalized units. The beam current was always 100 mA. The number of bunches was 480 during the scrubbing run and 240 before the scrubbing run. PETRA III was set-up in the 240 bunch mode with an horizontal emittance of about 1 nm. During the scrubbing run the horizontal emittance increased from initially 2 nm to 4 nm. The vertical emittance decreased from 104 pm to 33 pm (red line). The increased emittance is an evidence for effects due to electron clouds although the beam dynamics is not understood.

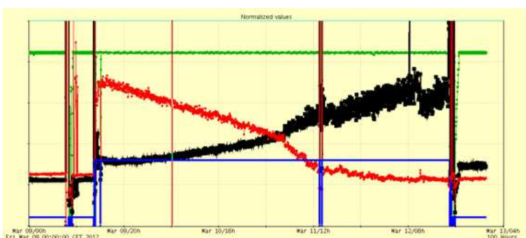

Figure 8: Screen shot of the archive data viewer, showing the the beam current (green line), the number of bunches (blue line), the vertical emittance (red line) and the horizontal emittance (black line)

Benefits from scrubbing

The conditioning of the vacuum chamber surface due to beam operation with a total integrated beam current of about 1000 Ah at the end of 2011 and the two dedicated scrubbing runs in March 2012 resulted in extended possibilities for the filling schemes without emittances growth, see Fig. 9. In 2012 it was possible to fill 320 bunches with a bunch to bunch spacing of 24 ns and a total beam current of 100 mA without a vertical emittance degradation while in 2011 this was only possible with a bunch spacing of 32 ns. Furthermore it is now possible to use a filling scheme with 60 bunch trains with 5 bunches while in 2011 it was only possible to use trains with 4 bunches without an emittance increase. But a filling pattern with 60 bunch trains with 6 bunches still showed a significant vertical emittance increase. Also the filling scheme with 480 bunches (Fig. 7), which was used during the scrubbing runs, is not suitable for user operation. Nevertheless the influence of the scrubbing runs on the instability threshold is a strong evidence that the observed emittance growth results from electron clouds.

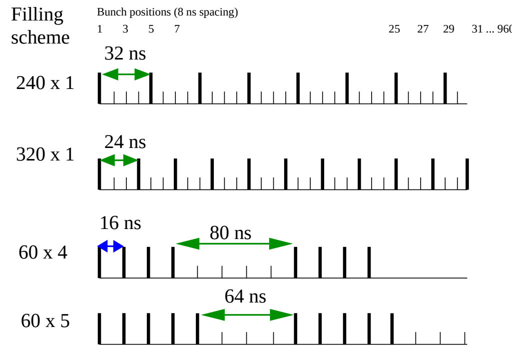

Figure 9: Bunch filling schemes without emittance growth in 2012. The total beam current is always 100 mA.

SIMULATIONS

Simulations of the build-up of an electron cloud in dipole vacuum chambers have been made with version 4.0 of the computer code ECLOUD [17, 18]. The vacuum chamber in the dipole magnets is modeled as an ellipse with a width of 80 mm and a height of 40 mm, see Fig. 3. The dipole field strength is 0.104 T. To solve the equation of motion the Runge-Kutta integration method was chosen within the ECLOUD code. Simulation results for the filling schemes with 60 short bunch trains with 4 and 6 bunches are shown in Fig. 10 for SEY of $\delta_{max} = 2.0$. The filling sequence of the bunch trains is clearly visible in the electron cloud intensity. From the measurements it is known that the filling scheme with 60 bunch trains with 4 is not suffering from electron cloud effects while the scheme with 60 trains with 6 bunches shows a strong vertical emittance increase. Therefore it is expected that the cloud density for the filling scheme with 60 times 6 bunches should be above the estimated threshold density of $1.4 \cdot 10^{12}\,\mathrm{m}^{-3}$ (see Eqn. 1 and Table 3), while the cloud density for the filling scheme with 60 times 4 bunches should be below this density. The simulated central density for the two filling schemes is shown in Fig. 11. During the simulated time interval this quan-

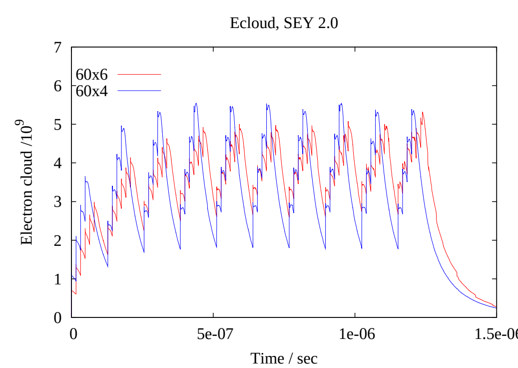

Figure 10: Simulation of the electron cloud for 60x4 (blue line) and 60x6 (red line) bunches for a total beam current of 100 mA and a SEY of $\delta_{max} = 2.0$.

tity fluctuates strongly between values below the instability threshold and values which are 10 times above the instability threshold. The strong fluctuations are most likely not only caused by the interaction of the positron bunch with the electron cloud but also due to the limited number of macro particles.

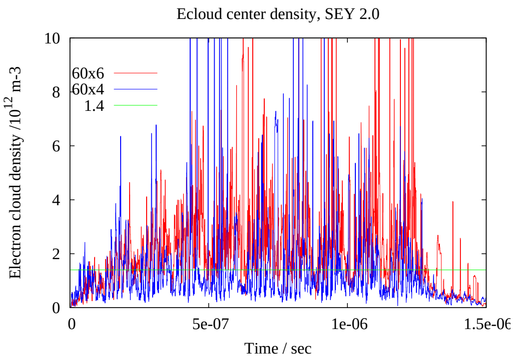

Figure 11: Simulation of the central volume density of the electron cloud for 60x4 (blue line) and 60x6 (red line) bunches for a total beam current of 100 mA and a SEY of $\delta_{max} = 2.0$. The green line corresponds to the threshold density of $1.4 \cdot 10^{12}\,\mathrm{m}^{-3}$.

A detailed view of the simulated central volume density of the electron cloud for the filling scheme with 60x4 bunches is shown in Fig. 12. In the same figure the number of electrons in the cloud (from Fig. 10) is also plotted in arbitrary units. The central cloud density is below the threshold density before the total number of electrons is increased from the emitted primary photoelectrons generated from the synchrotron radiation of each positron bunch. For the filling scheme with 60x6 bunches the central volume density of the electron cloud does not drop below the threshold density (see Fig. 13). This indicates that the measurements and the simulations are in agreement if one assumes that the maximum SEY δ_{max} is about 2.0.

CONCLUSION

At PETRA III a strong vertical emittance increase was observed in 2009 for bunch trains with 8 ns and 16 ns bunch to bunch spacing. The vertical emittance increase was strongly dependent on the bunch filling pattern and could be avoided if many short bunch trains with only 4 bunches or larger bunch to bunch spacing were used. A clear conditioning effect has been observed. While for the user runs filling patterns with 40 and 60 bunch trains with 4 bunches were used in 2010 it was possible to fill 240 equally space bunches with a bunch spacing of 32 ns in 2011.

In March 2012 two dedicated scrubbing runs with a total integrated beam current of about 10 Ah led to a further improvement of the situation. It is now possible to fill 320 bunches with bunch spacing of 24 ns and a total current of 100 mA without any significant emittance increase. The

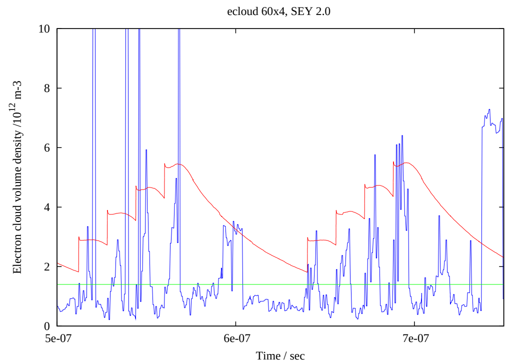

Figure 12: Detailed view of the simulated central volume density of the electron cloud for 60x4 bunches(blue line). The green line corresponds to the threshold density of $1.4 \cdot 10^{12}\,\mathrm{m}^{-3}$. Furthermore the total number of electrons in the cloud is shown in arbitrary units (red line).

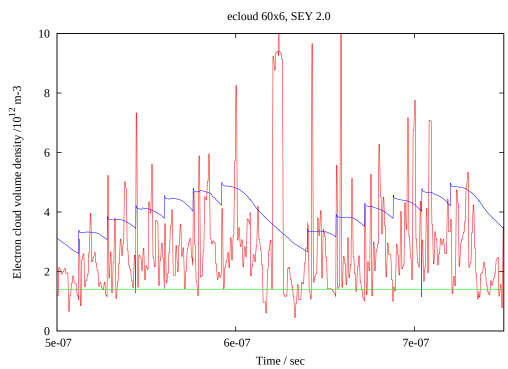

Figure 13: Detailed view of the simulated central volume density of the electron cloud for 60x6 bunches(red line). The green line corresponds to the threshold density of $1.4 \cdot 10^{12}\,\mathrm{m}^{-3}$. Furthermore the total number of electrons in the cloud is shown in arbitrary units (blue line).

influence of scrubbing runs on the instability threshold is a strong evidence that the observed emittance growth is related to electron cloud phenomena.

From measurements in the laboratory [11] the maximum SEY δ_{max} of the dipole chamber was initially (as received) 2.7. Simulations with version 4.0 of the ECLOUD code for different filling patterns indicate that maximum SEY is presently about 2.0.

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