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INFLUENCE OF INTRABEAM SCATTERING ON THE EMITTANCE OF PETRA III

J. Keil*, G. Kube, G. K. Sahoo, R. Wanzenberg, DESY, Hamburg, Germany

Abstract

PETRA III is a 6 GeV hard X-ray synchrotron radiation source at DESY in Hamburg (Germany) and is in user operation since 2010. The natural emittance of PETRA III is extremely low with 1.3 nm·rad and the coupling is typically less than 1 %. PETRA III is operated with a beam current of 100 mA using two different filling modes: a continuous mode with 960 bunches and a timing mode with 40 bunches. It has been observed that the horizontal emittance depends on the filling pattern and is in timing mode slightly larger compared to the emittance in the continuous mode. Despite the high energy of 6 GeV intrabeam scattering contributes for a slight emittance growth due to the small natural emittance and coupling of the machine. The increase of the emittance as a function of the single bunch current has been measured by using different filling patterns at a fixed beam current of 100 mA. The measurements of the emittance and the lifetime as a function of the single bunch current will be compared with theoretical expectations of the emittance growth due to intrabeam scattering and the Touschek lifetime.

INTRODUCTION

The 6 GeV synchrotron radiation source PETRA III [1] is in user operation since 2010. At the moment 21 user beam lines are installed which are using high brilliance photon beams solely from insertion devices. With a circumference of 2.3 km PETRA III is the largest of the existing 6 GeV storage rings in the hard X-ray range.

Two different filling patterns are mainly in use. In the continuous mode 960 equidistant bunches are filled. In this mode the lifetime of PETRA III is dominated by losses due to beam-gas scattering and is in the order of 10 h. In the timing mode 40 bunches are filled. In this mode the lifetime is only 1–2 h and is dominated by losses due to Touschek scattering. No ion clearing gap is used.

For both filling patterns PETRA III is running in top-up mode with a beam current of 100 mA. If the beam current drops by more than 1 % several injections with low charge are used to refill to 100 mA again. This helps to keep the variation of the single bunch beam current in the filling pattern small.

The natural emittance of PETRA III is rather low with $\epsilon_0 = 1.3$ nm·rad and the coupling is typically less then 1 %. The horizontal emittance measured at PETRA III is usually in good agreement with the expected value. Despite well corrected dispersion functions in the damping wiggler sections it has been observed, that in timing mode the measured emittance is often slightly larger compared to the continuous mode. In a machine experiment this effect has been studied in more detail.

EFFECTS INCREASING THE EMITTANCE

Damping Wigglers

In total 20 damping wigglers are installed in two straight sections of PETRA III to reduce the emittance by approximately a factor of 4. The poles of the wigglers are made from NdFeB permanent magnets and have a peak field of 1.5 T. Due to the damping wigglers the energy spread of PETRA III increases to $1.2 \cdot 10^{-3}$.

The emittances of PETRA III in both planes depend crucially on the well corrected horizontal and vertical dispersion in the damping wiggler sections and the arc with DBA cells and the extension halls. In the damping wigglers the dispersion function has to be smaller then $(D_x)_{\rm rms} \leq 20$ mm and $(D_y)_{\rm rms} \leq 5$ mm. Otherwise the horizontal emittance ϵ_x increases by more than 5 % and the contribution of the vertical dispersion to the vertical emittance is already $\epsilon_y = 10$ pm·rad [1].

For this reason the dispersion functions were corrected carefully before the measurements. A combined orbit and dispersion correction using all horizontal corrector magnets in the horizontal plane and 12 skew quadrupoles in the vertical plane have been used [2].

Resonances

The emittances will also increase if the betatron tune is near a resonance of the lattice. Especially the synchro-betatron resonances near the horizontal tune $Q_x + nQ_s = 37$ with $n \in \mathbb{Z}$ must be avoided. As the synchrotron tune Q_s is normally fixed the horizontal tune Q_x has to be selected carefully. For all measurements the same tunes have been used.

Ion Effects

Another effect which can provoke an increase of the emittances are trapped ions in the electric potential well of the electron beam. In case of poor vacuum conditions an ion-cloud related growth of the emittances has been observed. Ion effects appear above a current threshold which depends on the bunch pattern. During the measurements no indications of trapped ions have been observed.

Intrabeam Scattering

Intrabeam scattering (IBS) of the electrons within the bunch contributes also to the increase of the emittance. Because of IBS the emittances and relative energy spread

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* joachim.keil@desy.de

reaches a new equilibrium state [3], which is given for the emittance by

$$\epsilon_z = \frac{\epsilon_{z,0}}{1 - \tau_z / T_z} \qquad (1)$$

with $z = x$ or y and for the relative energy spread

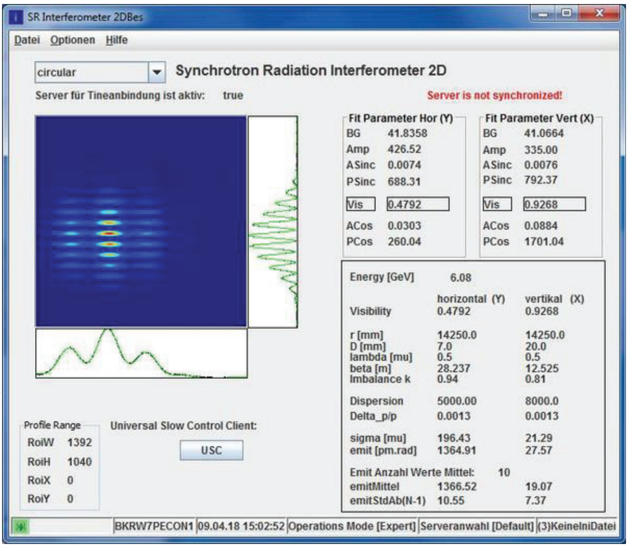
$$\sigma_p^2 = \frac{\sigma_{p,0}^2}{1 - \tau_p / T_p} \qquad (2)$$

and depends on the damping times $\tau_{x,y,p}$, the IBS rise times $T_{x,y,p}$ and the values at zero current of emittance $\epsilon_{z,0}$ and relative energy spread $\sigma_{p,0}$. The IBS rise times $T_{x,y,p}$ scale with $1/T \propto N/\gamma^4$, were N is the number of particles and γ is the Lorentz factor. The rise times T are long but not negligible compared to the damping times τ. A slight emittance increase is expected due to the small emittance and coupling at PETRA III.

EMITTANCE

For the measurement of the emittance two different instruments are available at PETRA III. At the diagnostic beam line in the von Laue Hall the size of the electron beam is measured by either using a pinhole optics or a high resolution compound refractive lens optics [4]. At a second diagnostic beam line a two-dimensional interferometer has been installed which is using the visible light of the synchrotron radiation of a dipole magnet [5]. A typical picture of the 2-D interferometer is shown in Fig. 1. From the measured beam sizes the emittances can be calculated using the beta functions and dispersion at the source point.

The same procedure to set up the machine for a regular user run has been used before the measurements. First a closed orbit correction was applied together with a precise local correction of the beam positions up- and downstream of the insertion devices (IDs) of the users. Afterwards the dispersion function was corrected as good as possible in the damping wiggler sections, the DBA cells and the extension halls. The gaps of the IDs were open during the measurements. The IDs would also contribute to the horizontal damping and would reduce the emittance further.



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Energy [GeV] 6.08

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beta [m]	28.237	12.525
Imbalance k	0.94	0.81
Dispersion	5000.00	8000.0
Delta_p/p	0.0013	0.0013
sigma [mu]	196.43	21.29
emit [pm.rad]	1364.91	27.57

Emit Anzahl Werte Mittel: 10

emitMittel	1366.52	19.07
emitStdAb(N-1)	10.55	7.37

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RoiH	1040
RoiX	0
RoiY	0

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Figure 1: Graphical user interface of the 2-D interferometer of PETRA III.

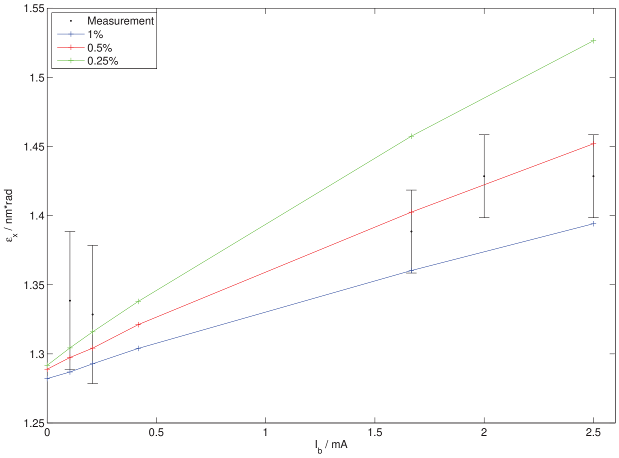

Figure 2: Horizontal emittance as a function of the single bunch current at 100 mA. Lines in color are simulated curves for different emittance ratios.

For each of the measurements the total beam current of 100 mA was distributed to a different number of bunches. The number of bunches was 960, 480, 120 and 40 bunches. Another measurement was done with a reduced current of 80 mA and 40 bunches. The single bunch current was therefore varied between 0.1 mA and 2.5 mA.

Because of the higher accuracy the 2-D interferometer was used for the emittance measurement. Unfortunately the vertical emittance showed large fluctuations which is still under investigation. It was only possible to estimate an upper limit of the vertical emittance of $\epsilon_y < 40$ pm·rad for all measurements.

The measurements of the horizontal emittance as a function of the single bunch current is shown in Fig. 2. A small increase of the emittance from 1.34 nm·rad at 960 bunches to 1.43 nm·rad for 40 bunches has been measured.

The command *ibsEmittance* of the program Elegant [6] has been used to calculate the emittance increase due to IBS for PETRA III. The calculations have been done for different emittance ratios $r = \epsilon_y / \epsilon_x$ of the horizontal emittance ϵ_x and the vertical emittance ϵ_y. The colored lines correspond to $r = 1\,\%$, $0.5\,\%$, and $0.25\,\%$. An emittance ratio of $\approx 0.6\,\%$ fits best to the measurements. This is in accordance with the expected coupling of PETRA III.

TOUSCHEK LIFETIME

For an independent check of the emittance ratio r the Touschek lifetime [7] can be used. Due to the small emittance and coupling of PETRA III Touschek scattering has a significant contribution to the total lifetime especially at high bunch currents. The reciprocal of the Touschek lifetime [8]

$$\frac{1}{\tau_T} = -\frac{N}{\gamma^2} \frac{r_e^2 c}{8\pi\sigma_x\sigma_y\sigma_s} \frac{1}{(\Delta p/p)^3} \cdot C(\xi) \tag{3}$$

depends on the number of particles N in the bunch, the classical electron radius r_e, the speed of light c, the Lorentz factor γ, the transverse beam sizes $\sigma_{x,y}$, the bunch length σ_s, and the momentum acceptance $\Delta p/p$. In addition it depends on the function $C(\xi)$ which slowly varies with the variable ξ. The variable ξ is defined as

$$\xi = \left(\frac{\Delta p/p}{\gamma} \frac{\beta_x}{\sigma_x} \right)^2 \tag{4}$$

and depends also on the momentum acceptance, which is approx. 1.6 % for PETRA III. The single bunch current $I_b = eN/T_0$ scales with the number of particles N, were T_0 is the revolution time and e the elementary charge.

The losses due to beam-gas scattering scale with the residual gas pressure. It has to be taken into account that the residual gas pressure $p = p_0 + p_1\, I$ has a current dependent component p_1 due to outgassing and is higher than the base pressure p_0 without beam. To have a constant value of p most of the measurements were done for a fixed current of $I = 100$ mA. The lifetime for the different filling patterns was determined after the steady-state of the pressure was reached.

The particle loss rate $\dot{N} = -N/\tau$ is proportional to the reciprocal of the total lifetime. The main contributions for particle losses in PETRA III are beam-gas scattering and Touschek scattering. The total lifetime can therefore be written as

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{gas}}} + \frac{1}{\tau_T} \quad . \tag{5}$$

The linear dependency $1/\tau_T \propto I_b$ of the reciprocal of the Touschek lifetime τ_T with the single bunch current I_b according to Eq. (3) can be used to separate the contributions of the lifetime between beam-gas scattering and Touschek scattering from Eq. (5).

Figure 3 shows the reciprocal of the total lifetime $1/\tau$ as a function of the single bunch current I_b. The beam-gas lifetime during the measurement was therefore $\tau_{\text{gas}} = 14$ h. The lifetime in timing mode ($I_b = 2.5$ mA) with 40 bunches is completely dominated by Touschek scattering whereas for 960 ($I_b = 0.1$ mA) the lifetime is dominated by beam-gas scattering. Nevertheless Touschek scattering reduces the lifetime also with 480 or 960 bunches slightly. For 480 bunches the lifetime is typically 9–10 h.

The dependence of the Touschek lifetime on the bunch length σ_z has been neglected. Measurements with a streak camera have shown that the increase in bunch length is only 15 % between 960 and 40 bunches [9].

For a comparison with theory the Touschek lifetime was calculated using command *touschekLifetime* in Elegant. The steady-state values of the emittances, the relative energy spread, and the bunch length calculated by the intrabeam scattering command were used as input values for the calculation. For the Touschek lifetime the local momentum acceptance of PETRA III was computed with Elegant. Realistic aperture limitations and a RF voltage of 20 MV have been used for the calculations.

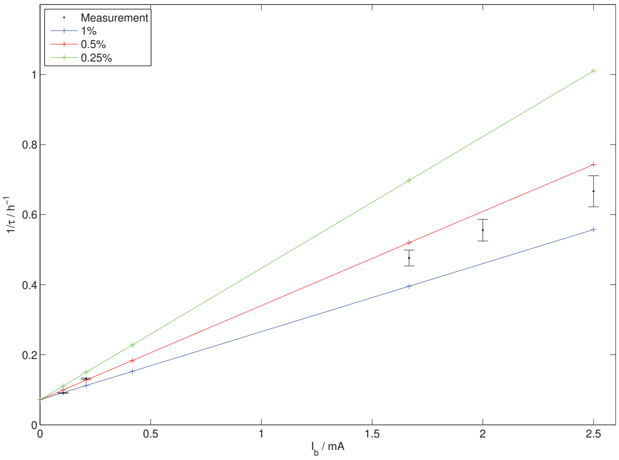

Figure 3: Reciprocal of the lifetime as a function of the single bunch current. Lines in color are simulated curves for different emittance ratios.

The reciprocal of the lifetime based on the calculation is plotted in Fig. 3 for three different cases of the emittance ratio $r = \epsilon_y/\epsilon_x$. Values of 1 %, 0.5 %, and 0.25 % have been used. For the theoretical curves a beam-gas lifetime of 14 h was assumed.

The curve of the Touschek lifetime with an emittance ratio of ≈ 0.6 % fits best to the measured values of τ_T. The value of the ratio r is in agreement with the values of the emittance increase due to intrabeam scattering.

SUMMARY

Despite the high energy of 6 GeV the influence of intrabeam scattering on the emittance of PETRA III cannot be neglected completely. The measurements have shown a slight increase from 1.34 nm·rad to 1.43 nm·rad of the horizontal emittance with the single bunch current from 0.1 mA to 2.5 mA which is in accordance with the expectation. The experiment has been performed under regular operation conditions for a fixed beam current of 100 mA. In addition the dependence of the Touschek lifetime on the single bunch current and the beam-gas scattering lifetime has been determined from the total lifetime. Comparing the measurements of the emittance and the Touschek lifetime with Elegant simulations it can be concluded that the emittance ratio was ≈ 0.6 % at the time of the measurement.

ACKNOWLEDGEMENT

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