BUNCH PURITY MEASUREMENTS AT PETRA III

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Abstract

Since 2010 the 6 GeV synchrotron light source PETRA III is in operation. With a horizontal emittance of 1.2 nm·rad, a coupling of typically 1 % and a total beam current of 100 mA the machine provides extremely brilliant synchrotron radiation for the users. For time-resolved measurements a filling pattern with 40 equidistant bunches with equal charge is used. To measure parasitic bunches between the main bunches two beamlines are equipped with avalanche photodiodes (APD) and time to digital converters (TDC) electronics. Besides parasitic bunches originating from the pre-accelerators of PETRA III it has been observed that initially empty buckets following the main bunch are populated. Measurements of the effect will be discussed and compared with simulations.

INTRODUCTION

PETRA III is a third generation synchrotron light source located at DESY in Hamburg, Germany [1]. Since its start of user operation in 2010 it provides hard x-rays from a 6 GeV electron beam for 14 beamlines. Recently it was upgraded to supply 10 additional beamlines in two new experimental halls in the North and East of PETRA. All beamlines use undulators as the radiation source. Due to the small horizontal emittance of 1.2 nm·rad and 12 pm·rad in the vertical plane PETRA III is one of the most brilliant light sources worldwide.

The beam current in user operation is usually 100 mA. For improved thermal stability the machine is operated in top-up mode with periodical injections every few minutes. An injection is carried out if the current drop exceeds 1 %.

Mainly two fill patterns are in use at PETRA III: In the *continuous mode* 960 bunches with 8 ns spacing are filled. In this mode the lifetime of 8 – 10 h is dominated by beam-gas scattering. In the *timing mode* 40 bunches with 192 ns bunch spacing are filled. Due to the higher bunch charge the lifetime in this mode is dominated by Touschek scattering and is between 1.2 – 1.6 h depending on the vertical emittance.

Bunch Purity

PETRA III is running in timing mode for nearly 50 % of the time. About half of all beamlines make use of this mode for time-resolved measurements. They require that the bunch purity of buckets in between the 40 main bunches is $< 10^{-5}$. The highest demands of 10^{-8} has the beamline P01 when doing nuclear resonant scattering (NRS) experiments.

For measuring the bunch purity an avalanche photo diode (APD) installed at the beamline P01 has been used. Amplified APD signals start a time to digital converter (TDC) which is stopped by the next bunch clock trigger. Both signals are processed by a constant fraction discriminator (CFD). The TDC has 4096 channels and a resolution of 115 ps per bin [2]. The TDC histogram of the photon arrival times is a direct measure of the time structure of the beam. The count rate has to be a small fraction of the bunch clock frequency. Otherwise the measurement is affected by the recovery time of the APD and by pile-up from multi-photon events.

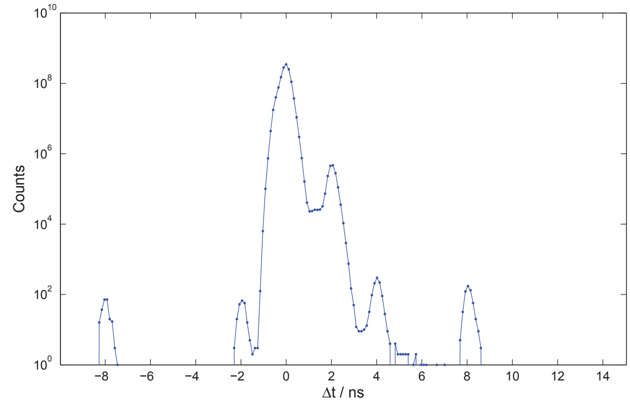

Figure 1: Typical TDC histogram with the main bunch at 0 ns and parasitic bunches in nearby buckets.

A typical TDC histogram measured during top-up mode over 15 min is shown in Fig. 1. Parasitic bunches have been cleared 1.4 h before. Besides the main bunch at 0 ns the highest parasitic bunch is at +2 ns with a purity of 10^{-3} followed by bunches at +4, ±8, and −2 ns. Due to the RF frequency of 500 MHz stable buckets are 2 ns apart.

SOURCES OF PARASITIC BUNCHES

Pre-Accelerators

A well-known source of parasitic bunches are the pre-accelerators of PETRA III [3]. In the Positron Electron Accumulator (PIA) several bunch trains from LINAC II can be accumulated before the beam is rebunched from 10.4 MHz to 125 MHz with a second RF-system. This generates ±8 ns bunches which are partially removed by a post-linac chopper (PLC). It consists of a fast deflector and an aperture limitation. Despite the high cleaning efficiency of the PLC some electrons can still survive.

Several other mechanisms of production have been identified and removed during the last years, like dark current from the LINAC II, electrons left over in DESY II from the last transfer (multiple of 16 ns) or a mismatch between the energy of the injected beam to the energy of DESY II at the time of injection (±2 ns).

During top-up mode parasitic bunches are injected into PETRA III with a constant fraction k together with the main bunches. The growth rate of particles in the parasitic bunch

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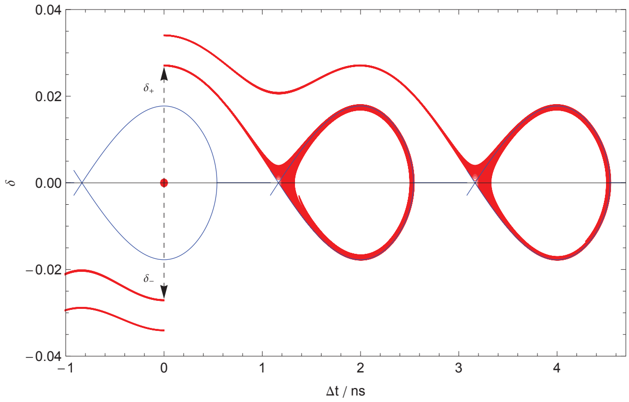

Figure 2: Recapturing of electrons in the longitudinal phase space after a Touschek scattering event.

depends on the lifetime τ (Touschek dominated) of the main bunches and the limit of reinjection $f = \Delta N_0/N_0 = 1\,\%$ and is

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = \frac{-f}{\tau \ln(1-f)} k N_0 = C_{\mathrm{inj}} N_0 \quad . \tag{1}$$

The growth rate $\dot{N}_1$ depends linear on the fraction k which depends on the clearing efficiency of the PLC. More bunches decrease N_0 and also decrease C_{inj} due to a longer lifetime.

Touschek Scattering

It has been observed that initially empty buckets following the main bunches gets populated when PETRA III runs with a stored beam without top-up. After a Touschek scattering event electrons outside the stable RF bucket can be recaptured in subsequent buckets if they lose enough energy due to radiation damping [4]. This process is shown in Fig. 2, were $\delta = \Delta p/p$ is the relative momentum deviation and Δt is the time lag to the main bunch.

Touschek scattering in the main bunch (red dot) produces a pair of electrons with $\delta_\pm$ momentum deviation (black arrows) with $\delta_- = -\delta_+$. Whereas the electron with $\delta_- < 0$ is always lost (red, bottom curves) there is a small chance for the electron with $\delta_+ > 0$ to be recaptured in subsequent buckets (red, top curves). The necessary condition is that δ_+ is within a small momentum window. The stable RF buckets are shown as blue curves. The bucket height of PETRA III is $\pm 1.78\,\%$ for a voltage of 20 MV, the momentum acceptance of the lattice has been measured and is 1.6 %.

The growth rate of electrons in the parasitic bunch $\dot{N}_1$ can be calculated from the Touschek lifetimes of the limits of the momentum window and is [4]

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = \frac{N_0}{2}\left(\frac{1}{\tau_t(\delta_{\mathrm{min}})} - \frac{1}{\tau_t(\delta_{\mathrm{max}})}\right) = C_0\, N_0 \tag{2}$$

and scales with the number of electrons in the main bunch N_0. The factor 1/2 takes into account that the electron with $\delta_- < 0$ is always lost. Typical operational parameters of PETRA III in the timing mode have been used to compute the growth rate factor C_0 listed in Table 1. The calculation was done with the Touschek module in MAD-X [5].

Table 1: Momentum windows for recapturing (δ_{min}, δ_{max}), window width $\Delta\delta$ and impurity growth rate factor C_0 for two nearby buckets at 95 mA.

Δt	+2 ns	+4 ns
δ_{min}	0.02673	0.03370
δ_{max}	0.02699	0.03391
$\Delta\delta$	$2.6 \cdot 10^{-4}$	$2.1 \cdot 10^{-4}$
C_0	$3.6 \cdot 10^{-3}\ \mathrm{h}^{-1}$	$1.4 \cdot 10^{-3}\ \mathrm{h}^{-1}$

Measurements using a stored beam without top-up have shown that only bunches at +2 and +4 ns are growing. The required momentum deviation δ_+ for the recapturing in buckets with $\Delta t \geq 6$ ns would be so high, that electrons are outside the transverse momentum acceptance of the magnetic lattice. The impurity growth rate factors are therefore only upper limits. The electrons are lost within a fraction of a turn; the recapturing process itself needs several turns to complete.

TIME DEPENDENCY OF THE BUNCH PURITY

The number of particles in the main bunch N_0 is essentially constant during top-up mode and $\dot{N}_0 = 0$ can be assumed on average.

For a parasitic bunch the situation is different: On one hand the bunch gets particles from a bucket change or during the transfer from the pre-accelerators. On the other hand particles are lost due to beam-gas and Touschek scattering characterized by the lifetimes τ_g and $\tau_t(N_1)$. The Touschek lifetime in addition depends on the number of particles. Therefore the differential equation of N_1 is

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = -\frac{N_1}{\tau_t(N_1)} - \frac{N_1}{\tau_g} + (C_0 + C_{\mathrm{inj}}) N_0 \quad .$$

Touschek scattering in the parasitic bunch can be neglected due to the small number of particles. The differential equation for the bunch purity ratio $r = N_1/N_0$ simplifies to

$$\frac{\mathrm{d}r}{\mathrm{d}t} = -\frac{1}{\tau_g} r(t) + (C_0 + C_{\mathrm{inj}})$$

which has the solution

$$r(t) = (C_0 + C_{\mathrm{inj}})\tau_g \left(1 - e^{-\frac{t-t_0}{\tau_g}}\right) \quad . \tag{3}$$

After a long time r approaches the equilibrium purity $r_\infty = (C_0 + C_{\mathrm{inj}})\tau_g$ with a rise time equal to the beam-gas lifetime.

The long term behaviour of the bunch purity $r(t)$ over several days of top-up operation is shown in Fig. 3. After an increase within one day the purity of the parasitic bunches are almost constant. The highest equilibrium purity have bunches at +2 ns and +4 ns and are produced by recapturing in buckets following the main bunches. All other parasitic bunches (±8 s and −2 ns) are produced in the pre-accelerators of PETRA III and their growth rate can change with time due to drifts of the timing of the PLC or DESY II.

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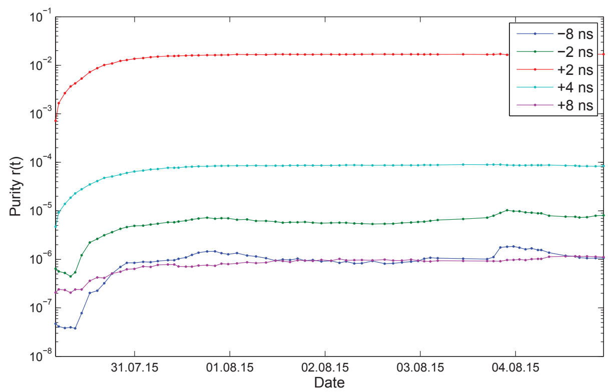

Figure 3: Long term behaviour of the bunch purity of relevant parasitic bunches during top-up mode.

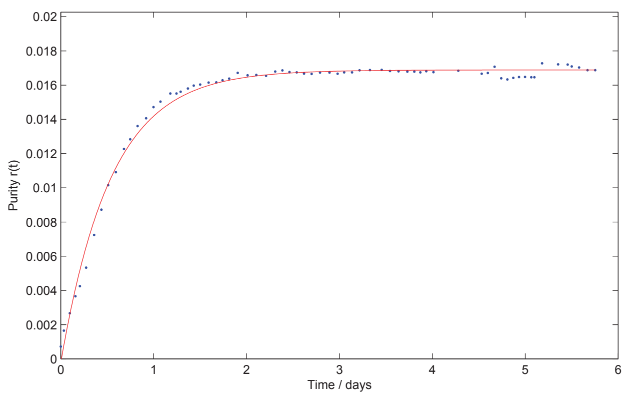

Figure 4: Time dependency of the bunch purity of the +2 ns bunch.

The unknown parameters of (3) can be determined by using a least-square fit to the time development of the purity data. Using the bunch at +2 ns as an example a growth rate factor of $C = C_0 + C_{inj} = 1.3 \times 10^{-3}\,\mathrm{h}^{-1}$ and a beam-gas scattering lifetime of $\tau_g = 13\,\mathrm{h}$ is calculated, see Fig. 4. For the +4 ns bunch the values are $C = 5.8 \times 10^{-6}\,\mathrm{h}^{-1}$ and $\tau_g = 15\,\mathrm{h}$. Whereas the beam-gas scattering lifetime is in agreement with expectations the measured growth rates are always smaller than the simple calculation shown in Table 1 due to the limited transverse momentum acceptance of the lattice.

Besides the parasitic bunches at +2 and +4 ns the bunch at +8 ns from the pre-accelerators is bothersome for the users. From the equilibrium purity $r_\infty = 10^{-6}$ a growth rate factor of $C = 7.7 \times 10^{-8}\,\mathrm{h}^{-1}$ can be calculated. With the lifetime of $\tau = 1.6\,\mathrm{h}$ at 100 mA in 40 bunch mode a transfer fraction of $k = 10^{-7}$ can be determined from (1).

PARASITIC BUNCH CLEANING

To achieve a bunch purity of less than 10^{-5} during top-up mode in PETRA III is rather challenging and requires an active cleaning. With the help of the vertical multi-bunch feedback system [6] a clearing of the parasitic bunches has been implemented. A vertical betatron oscillation of the parasitic bunches is resonantly excited and particles get subsequently lost on vertical aperture limitations. The resonant cleaning makes use of the separation of vertical betatron tunes between the main bunches and the parasitic bunches of $\approx 3.9\,\mathrm{kHz}$ in the 40 bunch mode at PETRA III [7]. It originates from wake fields generated by induced currents in the narrow gap vacuum chambers of the damping wigglers and undulators.

By using a single frequency sweep near the vertical tune in a 500 ms time span only the parasitic bunches can be removed. The cleaning is done together with the top-op injections and is repeated in regular intervals. The small remaining excitation of the main bunches during cleaning can be minimized by carefully optimizing the time span and the amplitude of the excitation.

SUMMARY

Measurements of the bunch purity using a detector system at the beamline P01 have been used to identify the different sources for parasitic bunches in PETRA III. They are either generated in the pre-accelerators (typically ±2 ns and ±8 ns side bunches) and transferred together with the main bunches during top-up mode into PETRA III. Bunches behind the main bunches at +2 ns and +4 ns are produced by a recapturing process after a Touschek scattering event in the main bunch. With the vertical multi-bunch feedback system the cleaning of parasitic bunches is possible but has the drawback of shortly exciting the main bunches.

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