EMITTANCE MANIPULATIONS AT BESSY I

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Abstract

At the synchrotron radiation light source BESSY I transverse and longitudinal emittances are routinely increased in order to reduce lifetime limiting Touschek losses. In the longitudinal plane the phase of the RF cavity voltage is modulated close to three times the synchrotron frequency. The transverse emittance is increased by exciting vertical dipole oscillations. Experimental results will be presented based on beam loss rate measurements as functions of the excitation frequency and the beam current. The observed resonant reduction of the loss rate can be explained by a parametric resonance processes and in addition by Landau damping in the vertical plane.

1 INTRODUCTION

Synchrotron radiation light sources are multi-user facilities serving a large variety of users with different requirements. Conflicts in the operation and the fine tuning of the storage ring arise because for example the demand for high brilliance of the photon beam requires small transverse and longitudinal emittances. The resulting high density of electrons within the bunches leads to high electron-electron scattering rates. Especially small emittance storage rings running at low energy suffer from this so called Touschek effect. In this process transverse momentum can be transferred and boosted to the longitudinal plane where the acceptance is usually limited by the hardware. Short lifetimes on the other hand are not acceptable by most other users.

The usual approach to overcome these losses has been the reduction of the electron density either by lengthening the bunches with a higher harmonic cavity or by increasing the vertical emittance with skew quadrupole magnets through transverse coupling. Both techniques require additional hardware not available at the 800 MeV BESSY I storage ring. Therefore, beam excitation techniques are used successfully with the advantage that the emittances can be varied by a large amount simply by turning the excitation levels up or down. This has increased the lifetime by a factor of three and the technique is very flexible since the emittances can be traded against each other in the most suitable way[1].

2 EXCITATION OF THE BEAM

It is obvious that the beam emittance can be increased by an external excitation similar to the kicks arising from the random emission of photons. This excitation would have to be very broadband in order to act differently on individual electrons within a bunch. It is less obvious that the excitation of an ensemble of electrons at fixed frequency can also lead to an increase of the emittance.

2.1 Longitudinal Plane

In the longitudinal plane the phase or the amplitude of the cavity voltage have been modulated successfully by introducing sinusoidal signals close to but below multiples of the synchrotron frequency into the corresponding feedback loops of the cavity RF systems. In the daily operation at BESSY the excitation frequency is close to three times the natural synchrotron frequency and producing about 10 % modulation of the cavity phase.

During the experiments presented in Fig. 1 the modulation frequency was swept through the resonance and lost particles were counted with a couple of beam-loss monitors placed at strategic locations around the ring. The loss rate displayed in Fig. 1 is dominantly produced by Touschek scattering events since this particular monitor is placed on the outside of the ring behind the dipole magnet following the mini-beta straight section. The detector is usually employed for the detection of the resonant spin depolarisation during the high precision determination of the energy[2]. The

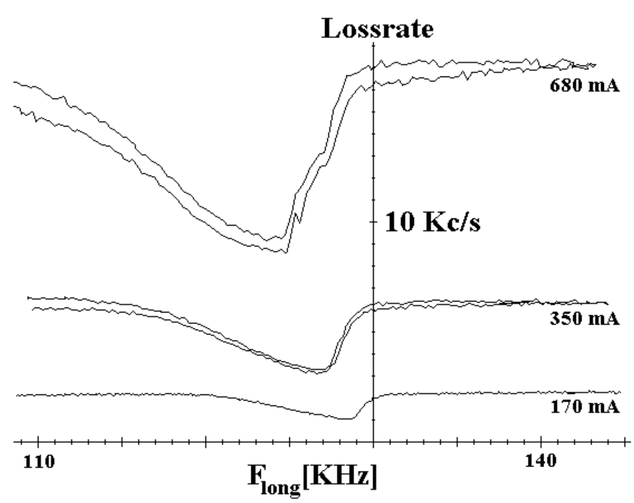

Figure 1: The loss rate of electrons as a function of the frequency, F_{long}, used for modulating the RF voltage phase. There is only a small shift if the resonance is scanned up or down. On resonance the loss rate is reduced and the lifetime of the beam increases by a factor of two. The minimum shifts up in frequency as the current goes down. This is compensated by a feed-forward loop.

reduction of the loss rate indicates an increase of the longitudinal emittance. In addition on resonance the amplitude of the 3 GHz component of the beam spectrum goes down by a factor of two. Longer bunches are longitudinally more stable and the spectral lines from the rigid dipole and quadrupole oscillation modes are damped by 10 dB. This is probably the reason why the horizontal beam size observed at a location with non-zero dispersion does not increase. The enlarged longitudinal emittance is compensated by the 3 times smaller dipole oscillations of the bunches. The result presented in Fig. 1 has been obtained in multi-bunch mode. Single bunches behave very similar.

2.1 Transverse Planes

The excitation of the beam in both transverse planes is accomplished by a 100 W amplifier connected to a single stripline terminated into 50 Ohms. In the routine operation of the storage ring a noise generator with a bandwidth of 300 kHz centred around the vertical resonance frequency of 1.35 MHz, corresponding to the tune Q_0=3.281, is fed into the amplifier. The excitation level is chosen to produce an increase of the vertical beam size by roughly a factor of two. This is monitored by the optical imaging system and it is accompanied by a similar improvement of the lifetime.

In Fig. 2 the loss rate normalised to the beam current is displayed again as a function of the excitation frequency. During this experiment 70 consecutive buckets out of the possible 104 buckets were filled. There is a hysteresis effect at the high frequency corner depending on the direction of the scan through the resonance. This is in agreement with the sign of earlier tune-shift-with-amplitude measurements at BESSY[3]. It appears as if the high frequency corner is independent of the beam current. On the other hand the width is strongly current dependant similar to the effective energy spread introduced by the longitudinal multi-bunch instability mentioned above[4]. Experiments in single bunch mode do not suffer from this instability and the results are very similar to the multi-bunch case: The induced centre-of-mass (COM) motion is much smaller than the increase of the beam size and a large fraction of the effect depends linearly on the excitation level. With a single bunch the impact of the head-tail instability is however more evident. The synchrotron sidebands are more clearly visible in the loss rates than in the COM motion. The shifts of these lines are identical to what has been observed before[5].

The resonant reduction of the loss rate has also been observed by exciting the beam horizontally.

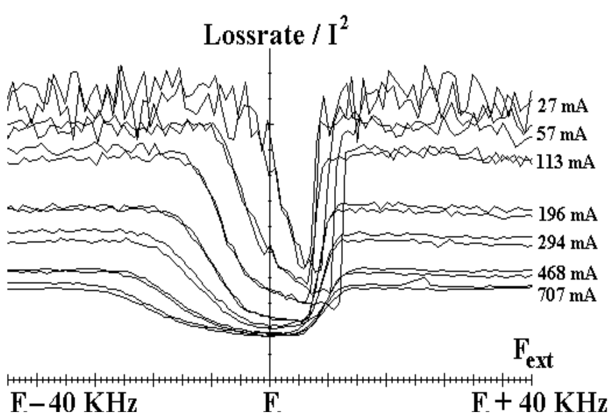

Figure 2: The normalised loss rate vs. the vertical excitation frequency, F_{ext}, and as a function of the beam current stored in multi-bunch mode.

2 THEORETICAL MODELLING

Standard many particle tracking has been used in order to get some insight into possible mechanisms turning a coherent excitation of the bunches into an incoherent increase of the emittance.

3.1 Longitudinal Plane

In the longitudinal plane the observations can be explained by the population of additional stable islands created by a parametric process. This is a non-linear effect based on the dependence of the synchrotron tune on the amplitude of the motion. The process has been analysed analytically for phase and amplitude modulated cavity voltages [6] and the lowest order resonance was investigated experimentally at the ALS [7]. The extension to an excitation close to three times the synchrotron frequency is straight forward. With the BESSY I parameters tracking calculations have been performed. The result of following 8000 particles over more than 5 natural damping times is displayed in Fig. 3. In this case a modulation depth of 10% and a frequency of 2.985 times the synchrotron frequency were selected. The population of the three additional islands is clearly visible. The temporary projections onto the energy axis or the longitudinal axis are asymmetric. Since the propeller-like structure rotates with the synchrotron frequency the energy spread and bunch length appear symmetric, non-gaussian, and broadened in reality. The longitudinal particle density is reduced, however, the increased energy spread has impacts on the line width of higher harmonics

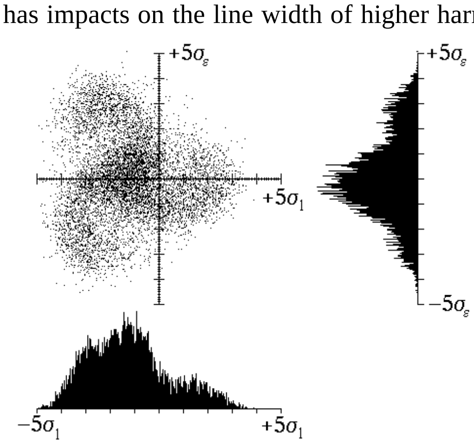

Figure 3: Longitudinal particle distribution with modulated cavity phase.

from undulator radiation. This is a disadvantage compared to higher harmonic cavities where only the bunches are lengthened.

3.1 Transverse Planes

In order to explain the remarkable observation that the COM motion is much smaller than the increase of the beam size the following effects have to be considered: Landau damping, the head-tail interaction, and the excitation of a parametric resonance.

Landau damping of an ensemble of particles is based on a distribution of the individual resonance frequencies. In case the ensemble is coherently excited the COM motion will remain small since the contributions from particles moving in- and out-of phase with the external force will nearly cancel. There is however an increase of the transverse emittance of the ensemble. In storage rings the tune of particle i at time t is given to second order by:

$$Q_i(t) = Q_0 + \xi_0 \cdot \delta p_i(t) + \xi_1 \cdot \delta p_i^2(t) + \frac{\partial Q}{\partial E_y} \cdot E_{y_i}(t) + \frac{\partial Q}{\partial E_x} \cdot E_{x_i}(t) + \ldots$$

with chromatic contributions, $\xi_{0,1}$, proportional to the individual relative momentum deviation, δp_i, and amplitude dependent terms proportional to the emittance of the particle, $E_{x,y}$. At BESSY the ξ_1-term has been extracted from measurements of the chromaticity: ξ_1=–820. The contribution to the tune spread with the natural energy spread of $5 \cdot 10^{-4}$ is much larger than the spread caused by the amplitude dependent effects since the emittances are rather small[3].

In reality the emission of synchrotron radiation does not only lead to the gaussian distributions of the individual amplitudes and the individual momentum deviations but also to a random walk of the particle within these distributions enhancing the Landau damping effect a little bit. This has been modelled by 4-dimensional many particle tracking. In Fig. 4 the impact of the external excitation on the amplitude, A, of the COM motion and the beam size, σ, are presented. 100 particles have been tracked over 5 damping times. The strength of the excitation is identical for all three curves. As expected without tune spread, corresponding to ξ_1=0, no effect on the beam size occurs. With increasing frequency spread the size is already bigger than the coherent motion of the ensemble. With larger tune spreads the COM motion will only a small fraction of the blown-up beam size just like observed. At BESSY there are additional contributions to the tune spread from the longitudinal excitation of the beam and the longitudinal instability. The spread of the tunes increase quadratically with the energy spread and linearly with the amplitude of the rigid dipole oscillation.

There are other effects which could explain the observations. The head-tail effect also turns a coherent excitation into an increase of the emittance of the distribution. Simulations, even with a simple two-particle model, show that below the instability limit the COM motion remains larger than the width of the distribution. Similarly to the longitudinal plane non-linear fields lead to tune shifts with amplitude. At certain excitation frequencies and excitation levels of the rigid dipole mode one additional resonance island appears and can be populated[8]. An indication of this effect is the observed hysteresis between up- and down scans. This is not analysed any further since the phenomenon is identical to the longitudinal plane.

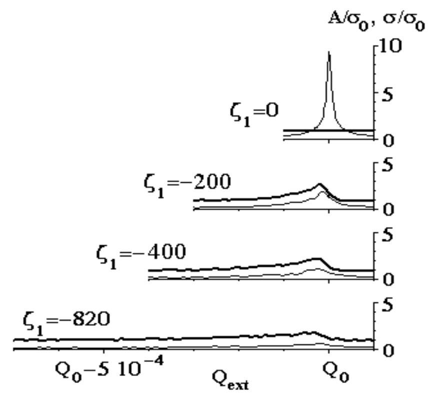

Figure 4: Amplitude of the centre-of-mass motion (thin line) and beam size (thick line) of an ensemble of particles as a function of the external excitation frequency.

4 SUMMARY

Longitudinal and transverse emittances in electron storage rings can be increased by coherent excitation of the beam. Processes like the population of parametric resonance islands and Landau damping suppress large coherent bunch oscillations at the expense of the desired emittance increase. The emittance can be controlled by selecting the appropriate excitation level. This is an advantage over the conventional techniques. The improved Touschek lifetime through the reduction of the particle density in one or the other dimension is highly appreciated by nearly all users of the synchrotron radiation source BESSY I.

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