# PERFORMANCE IMPROVEMENTS OF THE BESSY II STORAGE RING BY OPTIMIZING THE PHASE ACCEPTANCE*

P. Kuske[1†], J. Li, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany
[1] also at Humboldt-Innovation GmbH, Berlin, Germany

*Abstract*

Linear optics modifications in order to improve injection efficiency and for the installation of two IDs in one straight section demand an optimization of the sextupole correction scheme. Four harmonic sextupole families were sufficient with the earlier 8-fold symmetric lattice. Today there are ten families of harmonic sextupole magnets in addition to the three families of chromatic sextupoles. This paper describes our experimental approach to find better settings for these harmonic sextupoles based on the direct optimization of the injection efficiency with a longitudinal phase offset between storage ring and the injector - in our case a booster synchrotron. As demonstrated in the paper, the resulting improvement of the phase acceptance of the ring leads to increased momentum acceptance by suppressing 3rd order non-systematic resonances. This increases not only the injection efficiency for long bunches but also the Touschek lifetime, the largest contribution to the overall lifetime of low emittance storage rings.

## INTRODUCTION

During the last years two major changes were made to the 8-fold symmetric optics of the 1.7 GeV storage ring BESSY II. The first was the introduction of the so called injection optics: the horizontal ß-function, $ß_x$, in the injection straight was increased from 15 to 20 m and in the other 7 doublet straight sections $ß_x$ was reduced down to 10 m in order to improve the injection efficiency by mitigating the impact of long period APPLE II undulators in these locations. Recently, in one of the low beta straights equipped with quadrupole triplets, the vertical focus of the electron beam was shifted and an additional quadrupole magnet was installed in the centre of the straight in order keep $ß_y$ small to allow for the installation of two insertion devices, one in vacuum and one APPLE II undulator [1] with a fixed vertical vacuum chamber gap of 10 mm. These optics modifications break the lattice symmetry and in order to cope with the non-linear effects of the strong sextupole magnets, the existing 4 families of harmonic sextupole magnets were split up in 10 different groups of magnets. These magnets are placed in the straight sections where the dispersion is zero. Initially only a very coarse adjustment of sextupole settings was performed in order to recover the injection efficiency and the lifetime for the injection optics. The recent optics changes call for a better sextupole compensation scheme in order to fully exploit the potential of the lattice in terms of beam lifetime and injection efficiency. This is even more important for the fully funded BESSY VSR project where short bunches and thus shorter light pulses will be produced in the near future. Efficient injection of the comparatively long bunches delivered by the booster synchrotron requires a large momentum acceptance for particles oscillating with large horizontal amplitudes.

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† peter.kuske@helmholtz-berlin.de

## OPTIMIZATION STRATEGY

The BESSY storage ring is equipped with a traditional horizontal off-axis injection scheme [2,3]. Moving away from the optimum RF-phase between the injector synchrotron and the storage ring leads to large transverse and longitudinal oscillations of injected particles. If we now optimize the injection efficiency with the sextupole magnets we simultaneously search for a large transverse and longitudinal aperture. This is the basic idea of our acceptance optimization.

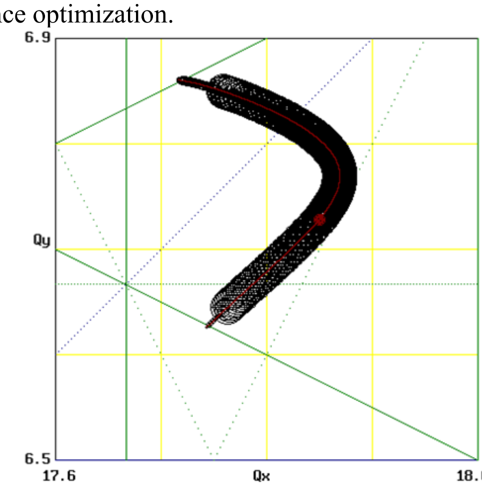


Figure 1: RF-steering: Tune variation. The red dot is the nominal working point and the radius of the circles corresponds to the actual beam current.

## EXPERIMENTAL RESULTS

Figure 1 shows the tune foot print of the beam as a function of the energy varied by RF steering. Off-momentum particles will encounter more or less harmful resonances. 2nd order resonances are shown in black, 3rd order resonances in green. Resonances are shown as straight lines if driven by normal or as dotted lines when driven by skew field components. Depending on the strength of these resonances particles may get lost by crossing them. With the broken lattice symmetry and before optimization the $Q_x+2Q_y$-resonance is most harmful and already reached with small negative momentum offset. In Fig. 1 most of the beam is lost when this resonance is approached. Similar to the situation at Diamond [4] it is this resonance together with the $3Q_x$-resonance which is the primary target for our optimization strategy.


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### *Phase Scans*

At BESSY II the RF-phase between the booster synchrotron and the storage ring RF can be reliably adjusted over more than one RF-period with a mechanical trombone. Only minor hysteresis effects show up. We observe the injection efficiency as a function of the phase offset adjusted with this trombone. The phase acceptance in terms of ns could be defined as the FWHM of the resulting curve.

With the help of the horizontal diagnostics kicker we are able to inject beam on-axis and without accumulating beam in the ring, because the beam from the previous injection shot will be kicked out by the kicker. The scan of the phase acceptance for the non-optimized sextupole settings is presented in Fig. 2. The acceptance appears to be quite large, however, the impact of resonances is still visible. Resonances become much stronger if the injected beam is accumulated by reducing the strength of the diagnostics kicker. The corresponding phase acceptance is much smaller and shown in blue in Fig. 3. With accumulation particles perform longitudinal synchrotron oscillations and large transverse oscillations if injected off-phase and the acceptance suffers much more from the poor sextupole settings.

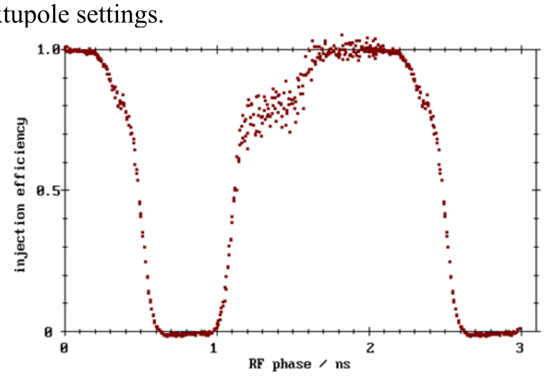


Figure 2: Impact of the RF-phase on the injection efficiency with on-axis injection and non-optimized sextupole settings.

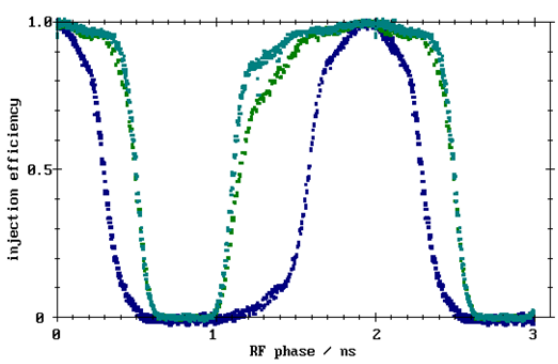


Figure 3: Accumulation efficiency as a function of the RF-phase with off-axis injection and non-optimized (blue) and after first and second optimization of sextupole settings (green and light blue).

### *Optimization the Phase Acceptance*

In order to improve the phase acceptance we move away from the point where the injection efficiency has already reached 100%, for example, to ~1.1ns or ~0.8 ns away from the optimum. An attempt failed to improve the injection efficiency at this point by directly targeting the resonance driving term of the Qx+2Qy-resonance with the help of appropriately handling the available harmonic sextupole magnets. Only a minor enlargement was achieved.

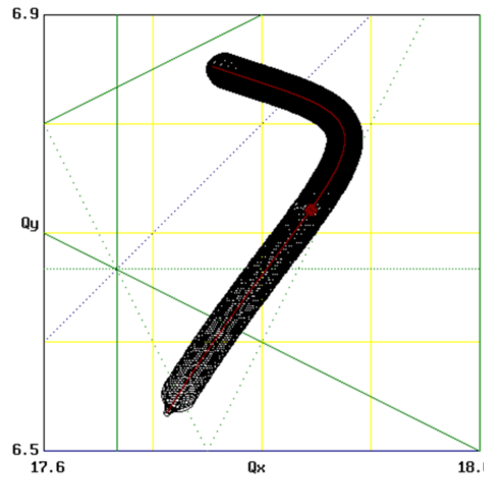


Figure 4: Tune variation by RF-steering: The $Q_x+2Q_y$-resonance can be crossed without losing beam. The width of the curve is proportional to the actual beam current.

Inspired by the extremely successful experimental optimization strategy, RCDS, the robust conjugate direction search developed at SLAC [5], we applied the first step of this approach. Even though the determination of the efficiency at BESSY II is a single shot measurement nevertheless we must average over many injections in order to get meaningful results. Thus this measurement is not faster than the lifetime determination of the stored beam which would be an alternative target. Optimizing one sextupole family after the other is hampered by the fact that we don't want to leave the usual hysteresis branch of our magnets. In the end we are looking for a set of values which after reloading and conditioning the magnets recovers the optimized performance. This will eventually also slow down the progress of the RCDS approach which we plan to apply in the future. So far we applied only the first step of this method and found a good starting vector for Powell's method. The progress after the first two iterations is shown in green and light blue in Fig. 3 and could be improved even further by individually optimizing sextupole families later on. The final situation is characterized in more detail in Fig. 4 in terms of the tune footprint created by RF-steering. Now the $Q_x+2Q_y$-resonance can be crossed without beam loss.

More important is the fact that the Touschek lifetime of the beam is increased considerably. A measurement of the lifetime of a Touschek dominated beam as a function of the RF-cavity voltage, which is equivalent to the RF-acceptance, before and after the sextupole optimization is presented in Fig. 5. The lifetime increases by more than 1 hour and the larger momentum acceptance is reflected in the shifted maximum of the black curve. Note, for small cavity voltage the momentum acceptance is determined by the RF-acceptance alone and both curves should overlap. You would expect a deviation in this region only in case the modified sextupole settings change the linear coupling.

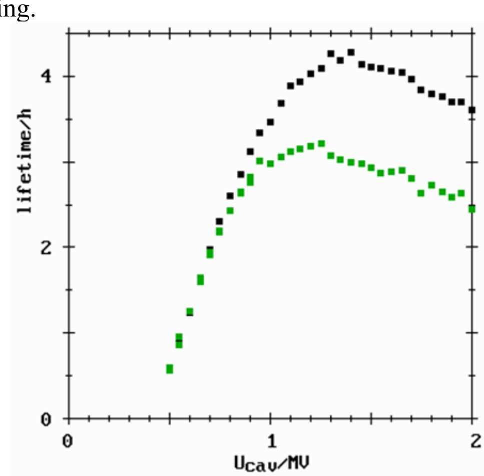


Figure 5: Lifetime dominated by the Touschek effect. Before (green) and after the optimization of sextupole settings (black).

### *Determination of the Momentum Acceptance*

The effective momentum acceptance can be extracted from the position of the peak in Fig. 5. In addition we used a set of phase acceptance scans taken as a function of the total accelerating voltage. The result of the measurements is shown in Fig. 6. The synchronous phase depends on the RF-voltage so that the curves are shifted. The width is either limited by the too low cavity voltage or the too small momentum acceptance of the lattice dominated by transverse effects. A comparison with simulations indicates an effective momentum acceptance for off-axis injection into the BESSY II storage ring around 3.3%. Results of these simulations are shown in comparison with the experimental results in Fig. 7 and explained in more detail in the figure caption.

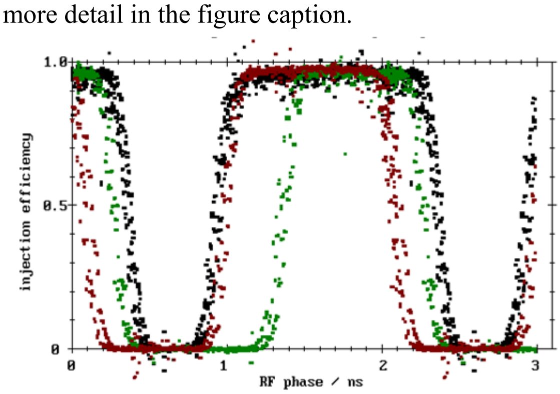


Figure 6: Phase acceptance for optimized sextupole settings and total accelerating voltages of 600, 1170 and 2100 kV (red, black and green).

## CONCLUSION

The optimization of the sextupole settings by looking at the injection efficiency while injecting off-phase between synchrotron and storage ring was very successful and straight forward. An advantage of this approach is the simultaneous optimization of longitudinal and transverse acceptance. This strategy leads to an improvement of the lifetime of Touschek dominated beams and the increased momentum acceptance will help to inject into the short bunches feasible with BESSY VSR. Based on the effective momentum acceptance of more than 3%, bunches in the booster synchrotron need to be only 3 times shorter compared to today (~60ps rms) in order to achieve 100% injection efficiency into the short bunches (~1.1ps rms) achievable with BESSY VSR.

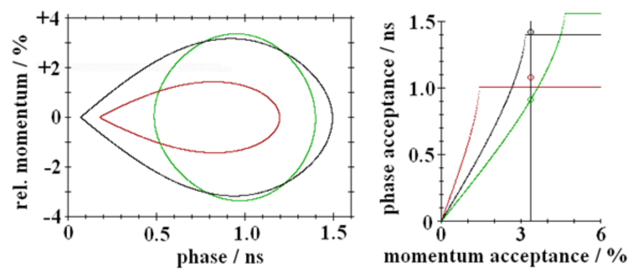


Figure 7: Left – longitudinal phase space at the limit of the momentum acceptance either given by the accelerating voltage (600kV in red, and 1170kv in black) or by the transverse limit (2100kV in green). Right – result of the simulation in comparison to the measured phase acceptance which are shown as circles with an assumed effective momentum acceptance of 3.3%. The phase acceptance for large momentum acceptance is usually limited by the available RF-voltage and the resulting RF dominated momentum acceptance.

The optimized sextupole settings found by this research are used now in routine operation and the improved Touschek lifetime is the most noticeable feature of this modification. Further studies using particle swarm optimization are under way to find sextupole settings which at the same time reduce the impact of IDs [6].

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