FREQUENCY MAP MEASUREMENTS AT BESSY*

P. Kuske, O. Dressler, BESSY, Berlin, Germany

Abstract

Frequency maps were measured under various operating conditions of the BESSY storage ring. Depending on the number and type of insertion devices in operation additional resonances show up. Details of the experimental setup, two dedicated diagnostic kicker magnets and a digital turn-by-turn, bunch-by-bunch beam position monitor (BPM) as well as the data analysis are presented. The results are in excellent agreement with theoretical calculations which are based on the linear model of the storage ring lattice extracted from the measured orbit response matrices. The non-linear lattice model had to be refined and now includes the fringe field effects of dipoles and quadrupoles and the systematic octupole and decapole components of the BESSY quadrupole and sextupole magnets.

INTRODUCTION

Frequency map analysis of the non-linear motion in accelerators either existing or in the design phase has proven to be a good tool for performance optimisation [1]. BESSY is a 3rd generation synchrotron light source based on a 1.7 GeV electron storage ring. The lattice consists of 16 double achromatic bends with alternating high and low horizontal beta functions, ß$_x$, in the straight sections, giving the unperturbed lattice an 8 fold symmetry. In addition to the three chromaticity compensating sextupole families there are four harmonic sextupole families in the straight sections where the dispersion is nominally zero. These sextupole magnets are set based on empirical experience [2]. Nowadays BESSY is fully equipped with insertion devices (ID) of various types: 4 strong superconducting (sc) wavelength shifters (WLS) including a 17 pole 7 T wiggler [3], 6 APPLE-type undulators which can introduce non-linear field components degrading the lifetime [4] and 6 planar IDs where the U125-wiggler also leads to noticeable performance reduction [5]. The frequency map analysis system was set up at BESSY in order to investigate the complex interplay of the many sextupole families, the IDs, and the lattice modifications for the fs-slicing project [6] or the installation of "super" bends in the future.

FREQUENCY MAP ANALYSIS SETUPS

Frequency maps are collections of dots in the tune space where each dot represents the fundamental frequency of one set of initial transverse offsets for the beam motion. A regular pattern in tune space can be obtained if the initial conditions are chosen appropriately and the excitation of resonances is small. Therefore, experimental frequency maps require two independent, fast and strong transverse kicker magnets in order to produce the initial beam conditions and a turn-by-turn beam position monitor (BPM) with an analysis for the fundamental frequencies of the two directions of the transverse motion.

Kicker Magnets

Two sinusoidal half wave kicker magnets with a total length of 0.55 m were installed over a ceramic chamber in one of the low ß$_x$ straight sections of the storage ring. The width of the pulse at the foot is 1.2 μs and larger than the revolution time of 800 ns. Thus a single bunch or a short (100ns) train of 50 bunches has to be used for the experiments. Up to the highest beam energy (>2 GeV) of the storage ring the maximum kick of >3 mrad in both planes can drive the beam to the aperture limitation. In the case of BESSY it was found advantages for regularly structured frequency maps to synchronise the kick and the experiment to the 50 Hz mains due to small unavoidable power supply ripples and their impact on the tunes.

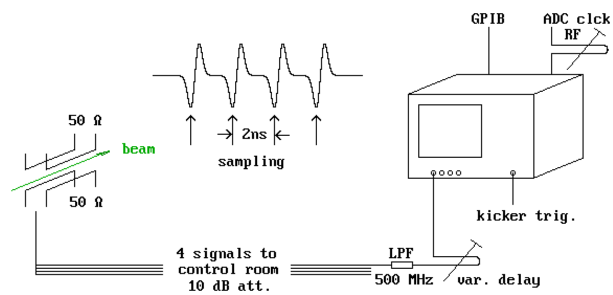

Fig. 1: BPM used for the frequency map measurements.

Beam Position Monitor

The setup of the digital BPM is shown in Fig. 1. The beam position can be measured turn-by-turn and bunch-by-bunch. A set of 4 striplines produces position dependent signals as shown in the insert of Fig. 1. The signals are guided to the control room and their delay can be mechanically adjusted. The negative peak signals are sampled with the LeCroy scope (LC684DXL) and the sampling is locked to the RF frequency (500 MHz). With the available 8-bit resolution of the scope's ADCs the beam position can be determined turn-by-turn with 40 μ uncertainty for a single bunch. A train of 50 bunches improves the resolution to 6 μ. In principle many shots could be averaged with the help of the scope however, in the experiments only a single shot for each set of initial conditions was acquired.

Control of the Experiment and Data Analysis

The experiment is controlled by a LabView program running on a PC connected to the EPICS based control system [7] and the scope (via GPIB). This program changes the kicker settings, controls the data transfer between the scope and the PC, and if needed injects new

* Work supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie and by the Land Berlin

beam at appropriate settings, i. e. for the momentum or with the ID gaps opened. The acquired data is stored and analysed on the PC. The fundamental horizontal and vertical frequencies are found by a conventional Fourier transform in combination with a refined peak finding algorithm. No window function is used for the fast decaying oscillatory experimental data.

Calculation of Frequency Maps

The calculations are based on the coupled linear model found by orbit response matrix analysis [8]. For the tracking calculations a symplectic code employing a 4th order integrator was developed [9]. Fringe fields of dipoles based on measured field maps and the theoretically expected fringe fields of quadrupole magnets [10] are included in the calculations. Even more noticeable in the frequency maps are the intrinsic octupole components of the BESSY quadrupole magnets [11]. The sextupole magnets are modelled by 7 kicks of different strength in order to represent the longitudinal field distribution. Random sextupole and decapole components created by the horizontal steering coils in the BESSY sextupole magnets are included based on the actual values of these correctors [12]. With the small tune shifts with amplitudes encountered in modern light source lattices with many sextupole families all these refinements are necessary in order to get good agreement between calculated and experimental frequency maps.

The small ID vacuum chambers (11 x 45 mm) determine the physical aperture. Even though the vertical gap is 11 mm a better agreement is found if this is reduced to 9 mm in the calculations. Tracking is done for 256 turns and the fundamental frequencies are determined with the same technique as in case of the experimental data except that a Hanning window is used for the Fourier transformation.

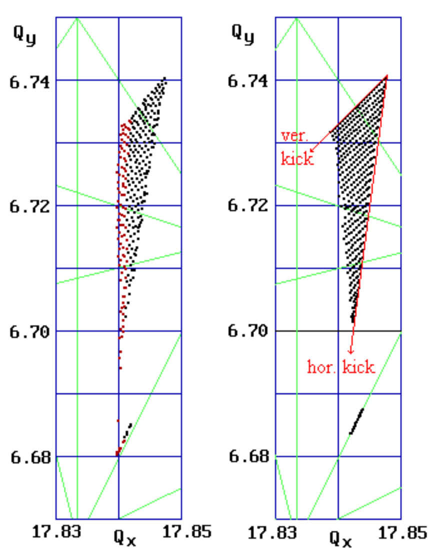

Fig. 2: Comparison of measured (left) and calculated (right) frequency maps. Resonances are shown up to the 6th order.

RESULTS

In Fig. 2 the comparison of measured and calculated frequency maps for nominal operating conditions, $\xi_x \approx \xi_y \approx +3$, without any IDs is shown. The experimental frequency map is on the left and red dots represent measurements where more than 2 % beam were lost. The overall agreement is excellent. In the theoretical map on the right the $2 \cdot Q_x$ - Q_y-resonance shows up due to small skew gradient errors only.

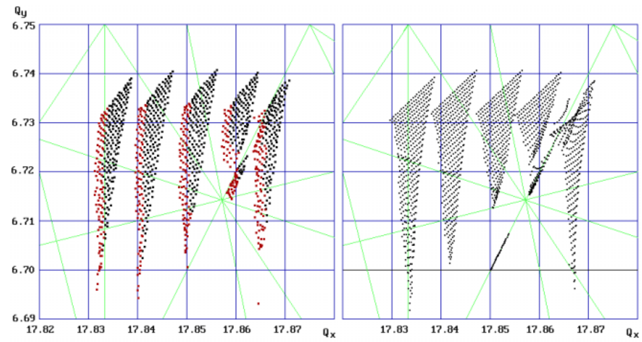

Fig. 3: Measured and calculated frequency maps as a function of the initial horizontal tune.

The appearance of this resonance was investigated in more detail as a function of the horizontal tune since at the nominal working point only dots corresponding to very small initial vertical kicks were found exactly on the resonance. The results are shown in Fig 3. The agreement between the measurements (left) and the calculations (right) shows that the model used for the calculation seems to correspond well to reality.

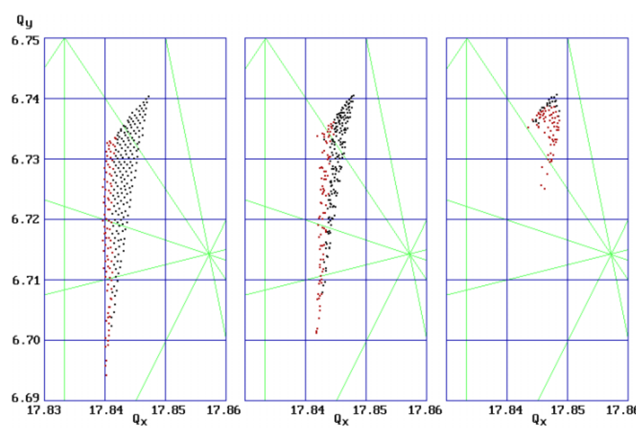

Fig. 4: Experimental frequency maps: left - without IDs, middle – with the sc WLS in operation and right – with one of the APPLE-type undulators in addition operating at smallest gap. Red dots correspond to measurements where more than 2 % of the initial beam has been lost.

In Fig. 4 the impact of insertion devices on the frequency maps is shown. The sc WLSs already lead to a noticeable reduction of the aperture. This appears to be a non-resonant linear effect created by the remaining beta beat after the compensation of the tune shifts and the physical apertures of the ring. With the UE56-undulator set to its smallest gap the dynamic aperture shrinks dramatically and so does the lifetime. Right now it is not clear whether the nearby 5th order resonance $3 \cdot Q_x+2Q_y$ is responsible for this behaviour. This decapole driven resonance could be excited by the non-linearity in the ID in connection with decapoles created by strongly excited horizontal correction coils. Since the installation of the sc WLSs the field compensation of the inner and the two outer poles is done partly by these nearby horizontal correctors giving them rather high values.

Momentum Dependent Frequency Maps

One of the dominating loss mechanism in low emittance rings is the Touschek effect. Colliding particles within one bunch transfer transverse momentum into the longitudinal direction which is boosted up by γ if transformed into the laboratory system and particles can escape easily the region of stable beam motion either purely longitudinally or in combination with a large horizontal betatron oscillation. The latter effect occurs if Touschek scattering takes place where the dispersion is non-zero. Even though this is rather unlikely in case of the BESSY lattice with the high particle density in the low $ß_x$ straight sections where the dispersion is close to zero, an experiment was performed as a function of the momentum with a fixed small vertical kick and an increasing horizontal kick [13]. The experimental results are displayed in Fig. 5. Since the horizontal kick was linearly increasing in amplitude the distance between the dots in frequency space is unequal. Due to the linear coupling errors the Q_x–Q_y- as well as the $3 \cdot Q_x+2 \cdot Q_y$-resonance are excited. If the WLSs are powered focussing errors brake the symmetry and the $2 \cdot Q_x+2 \cdot Q_y$-resonance is excited additionally.

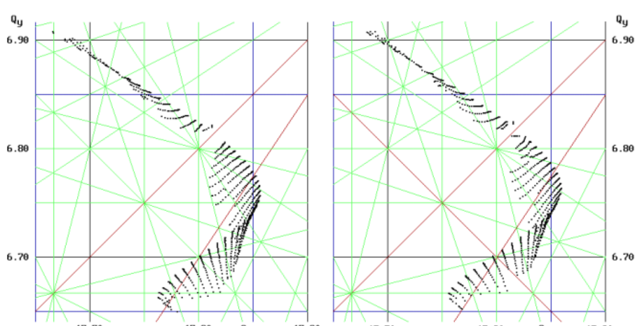

Fig. 5: Momentum dependent frequency maps under nominal operating conditions ($\xi_x \approx \xi_y \approx +2$). Left – without any IDs and right – with 3 sc WLSs in operation. Resonances are shown up to the 5th order and clearly excited resonances are displayed in red.

SUMMARY AND OUTLOOK

At BESSY, techniques for the experimental as well as the theoretical frequency map analysis have been developed. Data taking, data analysis, and the calculations are highly automated and very flexible. The predictions are in excellent agreement with the observations if a refined lattice model is used for the calculations. Modern 3rd generation light sources with many sextupole families demand a detailed modelling of all possible non-linear field components. The single particle beam dynamics at BESSY is influenced by a couple of resonances. Work will continue to assess their importance for the performance of the light source.

ACKNOWLEDGEMENT

We thank Jens Kuszynski for his continuous support for the LabView programming. Measurements of frequency maps require very stable beam conditions. Without the efforts of very many BESSY staff members these experiments would not have been possible. We thank them all. Discussions with D. Robin, A. Nadji, L. Nadolski, and M. Belgroune were very helpful and highly motivating.

REFERENCES

[1] H. Dumas, J. Laskar, "Global Dynamics and Long-Time Stability in Hamiltonian Systems via Numerical Frequency Analysis", Phys. Rev. Lett, 70, 2975-2979 and Proceedings of the Frequency Map Analysis Workshop, SOLEIL April, 2004: http://www.synchrotronsoleil.fr/francais/conferences/frequency%20map/index_fma.html

[2] J. Feikes, et al. "Beam lifetime optimisation of BESSYII by systematically adjusting the harmonic sextupoles", EPAC 2002.

[3] E. Weihreter, et al. "A 7T Wiggler for BESSY II: Implementation and Commissioning Results" this conference.

[4] P. Kuske, et al. "Investigation of non-linear beam dynamics with APPLE II-type undulators at BESSY II", PAC 2001.

[5] J. Feikes, G. Wuestefeld, "Lifetime Reduction due to Insertion Devices at BESSYII", PAC 2003.

[6] S. Khan, et al., "Status of the BESSY II Femtosecond X-ray Source", this conference

[7] J. Kuszynski, et al. "LabVIEW Based Data Acquisition, Control And Analysis Programs For BESSY As Versatile Tools For Optimization And Machine Controls", BIW 2004, to be published.

[8] W.J. Corbett, et al., "A fast Model-Calibration for Storage Rings", PAC 1993.
J. Safranek, "Experimental determination of storage ring optics using response measurements", Nucl. Instrum. Meth. **A388**, 27 (1997).

[9] L. Nadolski, thesis, unpublished

[10] E. Forest, J. Milutinovic, Nucl. Instr. Meth. **A269**, 474 (1988).

[11] T. Knuth, et al., "Results of Magnetic Measurements of the BESSY II Storage Ring Quadrupole Magnets", BESSY TB 210/97, April 1997

[12] M. Abo-Bakr, et al., "Results of Magnetic Measurements of the BESSY II Storage Ring Sextupole Magnets", BESSY TB 209/97, April 1997

[13] C. Steier, et al., "Measuring and optimizing the momentum aperture in a particle accelerator", Phys. Rev. E. Vol. 65, 056506.