INFLUENCE OF THE BESSY UNDULATOR ON THE BEAM DYNAMICS

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Abstract

The BESSY undulator is a pure REC Halbach-type structure. An ideal structure of this type is expected to produce a shift of the vertical tune and a vertical amplitude dependent tune shift. In reality the BESSY undulator additionally focusses the beam in the horizontal plane and couples the horizontal and vertical motion of the electrons. We present measurements of the linear and non-linear effects. The results are used as input parameters for tracking studies. Calculations of the lifetime as a function of the tune of the machine are in good agreement with our observations on the storage ring, if the synchrotron motion is included.

Introduction

The BESSY multiple wiggler/undulator (w/u) is a 35 period, pure $SmCo_5$-Halbach-type structure with a period λ_0 = 70 mm. The whole magnet structure is encapsuled in stainless steel and contained in a large ultra high vacuum chamber. Therefore the gap can be closed down to 6 mm [1, 2].

In the fourfold symmetric 800 MeV BESSY storage ring the w/u is installed in the straight section opposite the injection region. The injection takes place in the vertical plane, thus the vertical beta function is large at this location [3] (β_y=15m and β_x=3.5m). This is one of the reasons, why the gap of the w/u can only be closed to about 40 mm. For smaller gaps the lifetime of the stored beam becomes unacceptably short and even for machine studies it has to be larger than 18 mm in order to have a non-zero lifetime.

According to theory [4] the ideal magnet structure of the w/u would produce first order focussing by the small oscillatory electron motion and the modulation of the fields. These fields are non-linear and so is the focussing. If we assume that the electron wiggles in the horizontal plane and that the magnet blocks extend horizontally to infinity (k_x=0, k_y=k=$2\cdot\pi/\lambda_0$), the equation for the averaged vertical motion can be written as [5]:

$$\langle y\rangle'' = -\frac{1}{(4\cdot\rho^2\cdot k)}\cdot \sinh(2\cdot k\cdot\langle y\rangle)$$

$$\langle y\rangle'' \approx -\frac{1}{(2\cdot\rho^2)}\cdot\langle y\rangle - \frac{k^2}{(3\cdot\rho^2)}\cdot\langle y\rangle^3 - \ldots$$

ρ is is the radius of curvature in the maximum on-axis field (B_0). In line with this formula we would expect purely vertical linear focussing and some amplitude dependent tune shift from the lowest order non-linear, cubic term (octupole-like). This term will also drive forth-order resonances like $4\cdot Q_y$ = integer.

In contrast to these expectations, the BESSY w/u focusses in both planes with similar strength and the w/u acts like a skew quadrupole magnet. Our experimental results for the cubic term are in agreement with the theoretical expectations. It is the aim of this paper to present measurements of the linear and non-linear effects and to explain the observed severe reduction in lifetime by using the experimental results as input parameters for tracking studies.

Experiments

Linear effects of the BESSY w/u: tune shift

Measurements of the horizontal and vertical tunes for different gap settings of the w/u showed, that the insertion device focusses in both planes with similar strength, if the ratio of the beta functions in the straight section is taken into account. The results of the measurement are given together with the theoretically expected vertical tune shift in Fig. 1. The observed vertical tune shift is almost twice as large as expected and the positiv horizontal shift is not expected at all. In fact we would even anticipate a small defocussing effect in the horizontal plane from magnetic field measurements [6]. The reason for these discrepancies are field errors of the BESSY w/u.

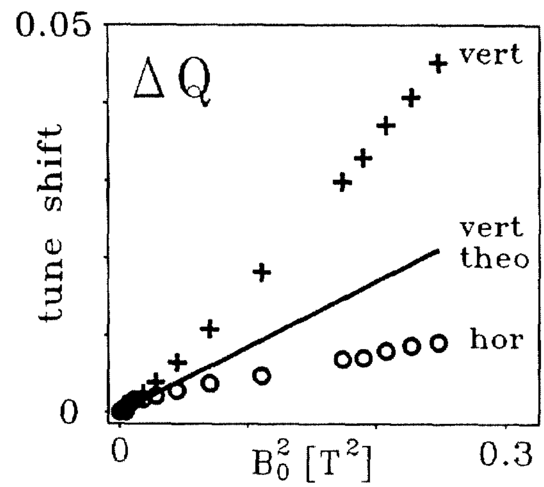

Fig.1: Tune shift induced by the w/u

Both tune shifts have to be compensated for, otherwise the tune would move too close to fatal resonances. We apply a local tune correction scheme, using the two quadrupole magnets on both sides of the insertion device. A small beta function beat is left, especially in the horizontal plane [7].

Linear effects of the BESSY w/u: coupling

The w/u unexpectedly acts on the electrons like a skew quadrupole magnet [8]. The horizontal and vertical motion of the electrons is coupled. As a consequence the vertical beam size enlarges and the optical image of the electron beam tilts as the gap is closed.

We have performed quantitative measurements of this "skew quadrupole" component. In the first experiment we used a variable closed orbit bump in order to pass the beam horizontally displaced through the undulator and we measured the vertical bending angle produced by the field errors. To first order, this angle is a linear function of the horizontal beam position in the undulator. The skew quadrupole components extracted from the slopes are shown in Fig.2 as circles. Since the position of the closed orbit is horizontally displaced with respect to the axis of this "skew quadrupole" magnet, we have to use a local feedback system to compensate for the gap dependent vertical orbit distortion [6].

A skew quadrupole drives resonances of the type $Q_x \pm Q_y$ = integer. We have used tune measurements close to the difference resonance, in order to estimate the coupling factor κ, which is proportional to the skew quadrupole component [9]. The mixing of horizontal and vertical motion leads to eigenfrequencies Q_I and Q_{II} which repell each other. The coupling factor κ is equal to the smallest distance between Q_I and Q_{II}. The skew quadrupole component of the w/u determined with this technique is shown in Fig.2 as crosses. The results of both experiments are in good agreement.

Close to the sum resonance the skew quadrupole field will reduce the lifetime. In this case, the beam is unstable within the stopband width, which is identical to the coupling factor κ.

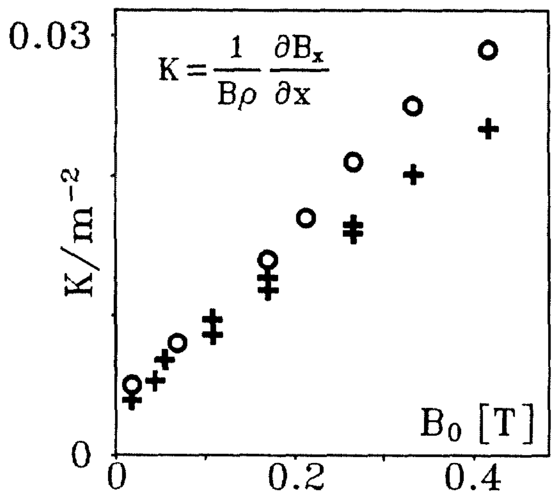

Fig.2: "skew quadrupole" field component of the w/u

The origin of this strong skew quadrupole component is the poor field quality of the BESSY w/u. A spread of remanence of the magnetic material produces a skew quadrupole field component. We did simulations for a spread of $\sigma = 2\%$, but even for larger spreads the estimated integrated skew quadrupole component is a factor 20 smaller than the measured one. The origins of this component are presumably the inhomogeneities of the magnetic material. The measured $\int B_x dz$ is in consonance with the observed deflection angle [6].

Non-linear effects of the BESSY w/u

The non-linear terms in the focussing properties have been investigated with two types of experiments. In the first experiment the tunes are measured as a function of the horizontal and vertical beam positions relative to the undulator. The pronounced parabolic dependence of the vertical tune as a function of the vertical beam position is used to extract the "octupole" component. This component is shown in Fig.4 as dots. We have not observed a significant sextupole component.

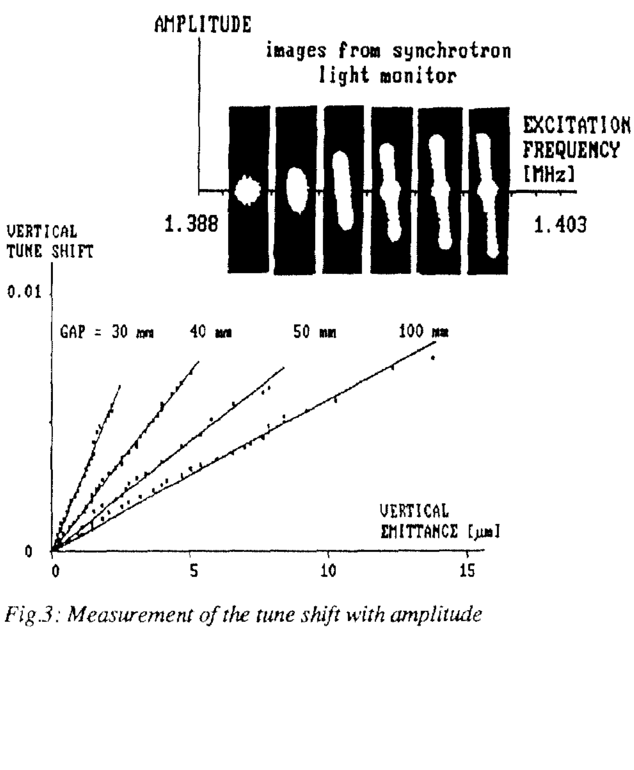

Fig.3: Measurement of the tune shift with amplitude

In the second experiment we determined the amplitude dependent tune shift with a technique brought to our attention by J.E. Perevedentsev. The beam is excited with a 200W-RF power amplifier and striplines and the steady state amplitude of the large electron oscillation is measured with an optical imaging system as a function of the excitation frequency. The RF power level is fixed during the experiment. The synchrotron light monitor is necessary, because the electrons can oscillate with a small and a large amplitude. This is shown in the top of Fig.3. We performed measurements for various gaps and obtained the following results: The extracted tune shift is always proportional to the square of the amplitude or the emittance (Fig.3 bottom). In order to determine the amplitude dependent tune shift due to the w/u, the contribution from other non-linearities in the lattice (the sextupoles have been switched off) has to be subtracted.

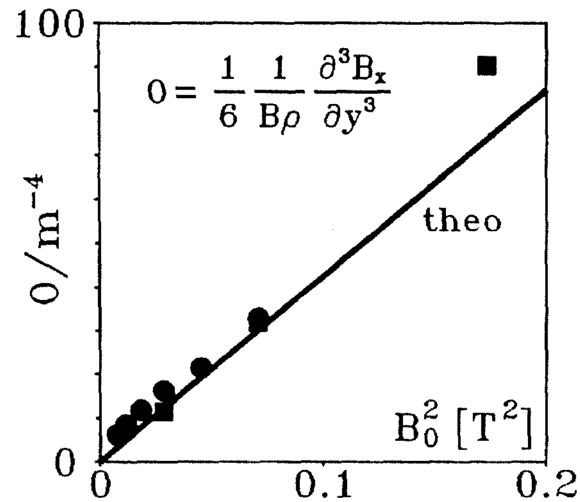

Fig.4: Octupole-like field component of the w/u

The experimental results have been used to evaluate the strength of a pseudo octupole component, which would produce a similar tune shift with amplitude. In Fig.4 these octupole-like components are displayed as squares. We find good agreement between theoretical (straight line) and experimental results.

Influence of the BESSY w/u on the lifetime

We have measured the lifetime of the stored electron beam as a function of the vertical tune close to our usual working point. The lifetime is expected to be influenced by the linear coupling resonance $Q_x+Q_y = 8$ driven by the skew quadrupole component and the resonance $4 \cdot Q_y = 9$ driven by the cubic term in the focussing force. The tune diagram in Fig.5 (left) shows these two dominating resonances. The working point is moved along the dotted line with two quadrupole families. The experimental result is presented in Fig.5 (right). We performed the measurements at very low beam current and with the sextupoles switched off. The influence of the $4 \cdot Q_y = 9$-resonance is clearly visible. Width and strength depend on the gap and the tune shift with amplitude is responsible for the asymmetric shape of the curves. When the tune approaches the coupling resonance $Q_x+Q_y = 8$ the beam is lost. The moderate reduction for vertical tunes around 2.26 is, as we will see from the tracking studies, not an additional resonance but a synchrotron sideband to the $4 \cdot Q_y = 9$-resonance.

Simple semi empirical model for tracking studies

We use a simple semi empirical model for theoretical studies of the lifetime limiting effects. This model is based on the experimentally verified linear optics calculations and the known physical aperture restrictions in the vertical plane: ±20 mm inside the dipole vacuum chambers and -20 mm at the injection septum magnet. In the tracking calculations the ring is represented by linear transfer matrices since the sextupole magnets were switched off during the experiment. The measurements were done at low beam current, therefore the dominant loss mechanism for particles is the elastic Coulomb scattering into the vertical plane and the lifetime is proportional to the square of the largest scattering angle for which the motion of the electron is still stable. This deflection angle is small at locations where the beta function is large. With the low emittance optics METRO this is the case in the long straight sections and the inner dipole magnets [3]. In the tracking studies we started particles at both locations and took the average for the calculation of the lifetime.

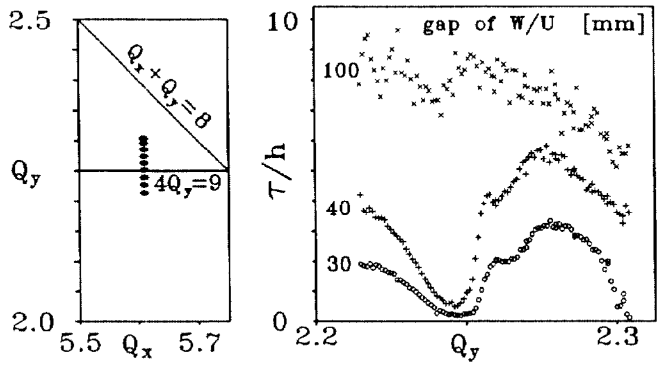

Fig.5: Tune diagram and measured lifetime vs. Q_y

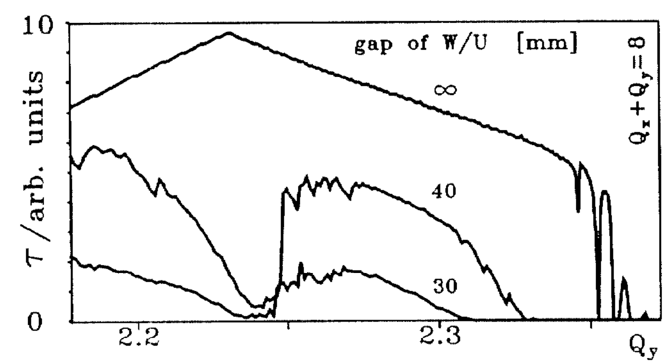

Fig.6: Calculated lifetime vs. Q_y

The contribution of the BESSY w/u to the particle losses was taken into account in the following way: The physical aperture in the straight section is determined by the undulator, if the magnetic gap is smaller than 44 mm. An ordinary skew quadrupole component of the measured strength (see Fig.2) and the theoretical cubic term in the focussing force, as verified experimentally (see Fig.4), is included in kick approximation into the tracking code at the center of the w/u.

The inclusion of higher multipole components like dodecapoles has no significant impact on the results. The tune modulation due to synchrotron motion has to be included, in order to get reasonable agreement with the experiment. We chose an energy deviation of $\Delta E/E = 10^{-3}$, which corresponds to twice the natural energy spread. The tunes are modulated sinussoidally with a depth given by the product of the chromaticities ($\xi_y = -6$, $\xi_x = -12$) and the energy deviation. The synchrotron tune is 1/150. A particle is considered stable, after it survives 200 synchrotron oscillations. This corresponds roughly to one longitudinal damping time.

The tracking results are shown in Fig.6. The fatal influence of the skew quadrupole component is clearly visible, even for a coupling factor of only 1 percent. This is the amount of coupling due to errors. If the gap is closed, the coupling and the stopband width of the $Q_x+Q_y = 8$-resonance increase. The neighborhood of the sum-resonance has to be avoided.

As expected, the cubic term in the focussing force is responsible for the dip at the $4 \cdot Q_y=9$-resonance. The tune shift with amplitude also leads to shorter lifetimes close to the coupling resonance. The additional dip for tunes between 2.25 and 2.26 appears in the calculation only if the longitudinal motion is included. Actually the lifetime reduction due to the $4 \cdot Q_y$-resonance is smaller by a considerable factor without the synchrotron motion.

In summary, the strong reduction of the lifetime for small gaps of the BESSY w/u is the combined effect of the deminished physical aperture, the skew quadrupole field component, and the cubic term in the focussing force.

Summary

Due to the large vertical beta function in the straight section of the BESSY storage ring, any additional horizontal magnetic field strongly effects the vertical motion of the electrons. Therefore, the beam could be used as a probe for field components of the BESSY w/u integrated along the path of the electrons. It turned out, that this insertion device contains additional components, which lead to horizontal focussing and which act like a skew quadrupole magnet. At BESSY the tune shifts and the closed orbit distortions are locally compensated for.

Experimental and theoretical studies showed, that the severe lifetime reduction for small gaps of the insertion device is caused by the skew quadrupole field component and the cubic term in the focussing force. There can hardly anything be done against this cubic term, because it corresponds to a pseudo octupole field component, like the one in the fringe field of quadrupole magnets [10], however, we are planning to combat the additional coupling introduced by the skew quadrupole component of the BESSY w/u.

Acknowledgements

The contributions of our guests, G. Isoyama, E. A. Perevedentsev, M. Zisman, F. Selph, and of our BESSY colleagues are greatly appreciated.

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