SLS Storage Ring Orbit Studies

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Contents

1 Abstract

The tune-shifts and the beam positions resulting from kicks on horizontal or vertical corrector magnets at the SLS storage ring [1] can be qualitatively well modeled with the Tracy-2 code [2]. The code allows simulation of beam properties of the undisturbed storage ring as well as after perturbation of the system. The code can therefore be used to predict beam behavior after varying corrector magnet strengths. Unfortunately the precision of these model predictions is not very high at the moment. Once the underlying technical properties are better understood, precise predictions of beam dynamics by using the Tracy-2 code will be possible. This resembles a well understood environment opposed to the sole application of LOCO Analysis [3] which leads to precise predictions of beam dynamics without necessarily enlarging understanding of the element errors.

2 Introduction

2.1 The Studies

The performed orbit studies and this report are the result of practical studies required by ETH for undergraduate students of experimental physics prior to taking final exams. I have spent four weeks learning practical aspects of experimental accelerator physics on site. In advance I acquired basic understandings of accelerator physics in the lectures ”Physics of Particle Accelerators” [4] given by Lenny Rivkin at ETH. The following report is a summary of the experiments and studies I carried out at the SLS storage ring. It contains a description of the experiments as well as analysis of the acquired data. Not all questions that arose during the experiments could be answered completely due to the short time frame given, but answers will be stated where they could actually be found. A complete error analysis hasn't been done because the systematic errors of the BPMs, corrector magnets, etc. couldn't be investigated during this short period of time.

2.2 The Accelerator

The Swiss Light Source SLS [1] is a dedicated high brightness synchrotron light source under construction at the Paul Scherrer Institute PSI in Villigen, Switzerland. The accelerator complex includes a 2.4GeV (low emittance) electron storage ring with 288m circumference, a full energy injector booster synchrotron and a 100MeV linear accelerator pre-injector. The facility will include a first set of five beam-lines when it is scheduled to start operation in August 2001. At the moment the storage ring is under commissioning.

2.3 Tracy-2 Software

Tracy-2 [2] is a programming environment to study single particle dynamics based on modern methods [5]. The version used at SLS is implemented with C/C++ derived form the original version that used Pascal-S code. All theoretical beam analysis was done using Tracy. The given SLS lattice design was fed as a device input file. The closed orbit could be generated with Tracy by entering known component values (corrector strength, quadrupole and sextupole settings, etc.), perturbations could then be applied to study development of beam properties under certain circumstances. The theoretical predictions that were compared with measured beam properties were developed completely using Tracy simulation.

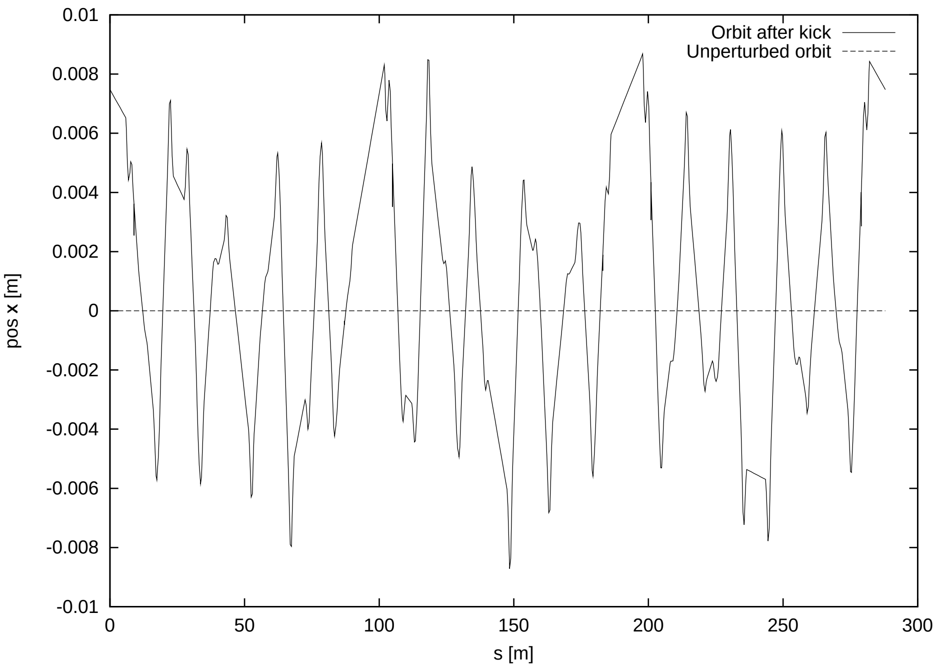

Figure 1: Beam oscillation in horizontal plane after kick on a horizontal corrector magnet.

3 A Peculiarity Detected in a Tracy Routine

One of the first perturbations I wanted to apply was a kick on a horizontal or vertical corrector magnet. These correctors are built onto the ends of sextupole magnets and are used to give the passing particles a kick, i.e. a deviation of their angle. This leads to an oscillation of the beam around the unperturbed orbit and therefore to a new closed orbit. Due to coupling of the horizontal and vertical planes of motion (in a non-linear machine, i.e. when sextupole magnets are switched on), an oscillation following a kick in one plane will also be visible in the perpendicular plane. Figure 1 illustrates the oscillation of the beam in the same plane the kick (1mrad horizontal) was applied. Figure 2 shows the coupling effect in the other plane - when looking at the scale it has to be considered that the amplitude of the oscillation due to coupling is much smaller. It is also very important to keep in mind that measurement of the beam position can only be done at the 72 beam position monitors (BPM) along the storage ring. In the experiment it is not possible to observe the beam position in every element as here seen in the theoretical plots in figures 1-4.

While simulating this effect in Tracy, I found an effect in beam position predictions which can only be understood when actually looking at the special approach of the Tracy code. Applying a vertical kick results in normal oscillation in the vertical plane. The oscillation in the horizontal plane however shows six

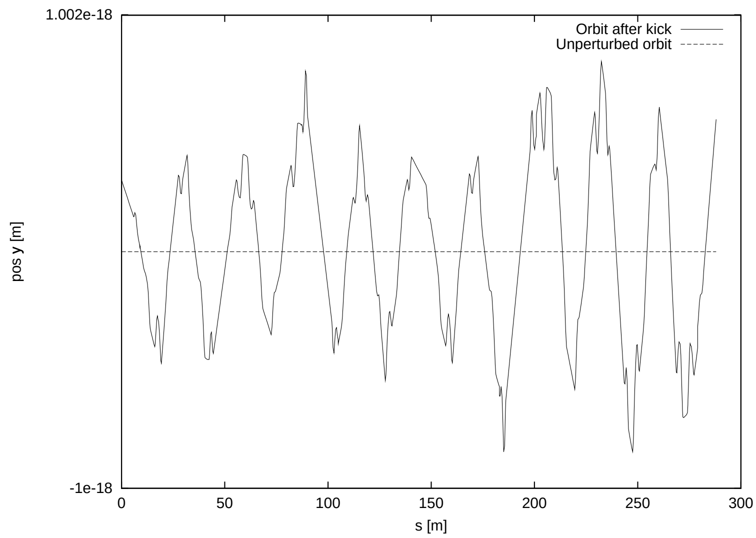

Figure 2: Beam oscillation in vertical plane after kick on a horizontal corrector magnet.

spikes which are of much higher magnitude than the amplitude of the oscillation (figure 3). These six spikes were found to originate in the skew quadrupoles. Skew quadrupoles are basically quadrupoles which are tilted (rotation axis is the beam-line) at a certain angle. Calculation of the beam properties in these skew quadrupoles is done by transforming beam coordinates (s, x, y) into the rotated system (s, x', y'), applying quadrupole fields and transforming back to the unrotated system. A kick given along one axis has two perpendicular non-zero components in this rotated system. If one looks at the beam position before transforming back to the unrotated system (as if one were sitting in the skew magnet system), it seems as if the original kick had a perpendicular component too, thus giving a much greater amplitude to the oscillation in the plane perpendicular to the plane of the original kick. If one takes into account that the beam position data calculated by the Tracy code is always indicated in the system of the measurement point, this leads to the spikes seen. Hence a rotated skew quadrupole magnet will make Tracy rotate the output at the position of the skew quadrupoles so that it is correct if seen in the skew quadrupoles system however not correct if compared to the other positions of unrotated elements. If the predicted position values of the skew quadrupoles are removed, the normal oscillation due to coupling is observed (figure 4) and shows that no change in the oscillation is generated by this "position displacement" due to the fact that it is only displaced when looked at from another system. Tracy calculations therefore remain correct.

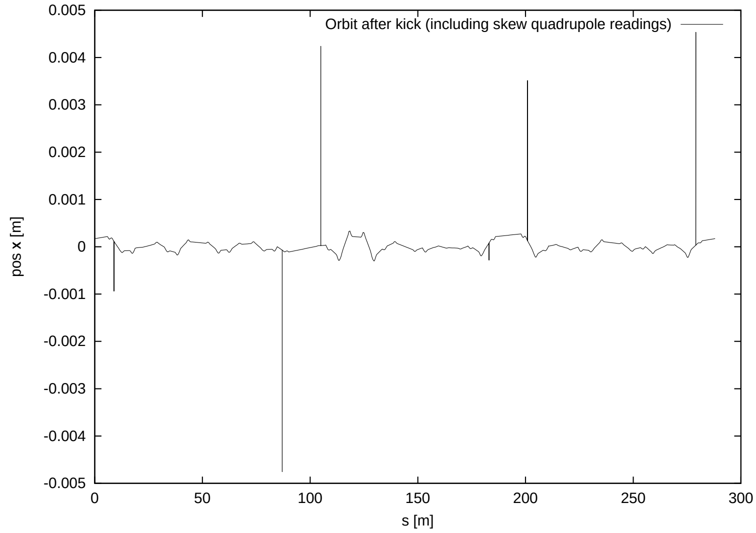

Figure 3: Beam oscillation in horizontal plane after kick on a vertical corrector magnet.

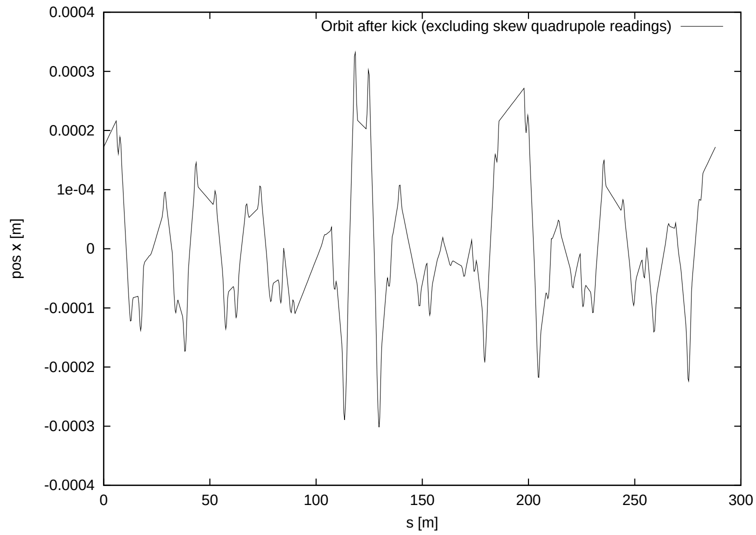

Figure 4: Beam oscillation in horizontal plane after kick on a vertical corrector magnet (suppressing skew quadrupoles).

4 Tune-shift and the Kick Conversion Factor

A general problem arises when comparing measurement data (after applying kicks) to theoretical predictions by Tracy: In experiments kicks are applied to the beam by giving a certain current on a corrector magnet. The current setting is in Amperes whereas the kicks in the Tracy model are applied in radians. Fortunately the current and the angle of the kick can easily be related. Recall the *magnetic rigidity* $B\rho$ defined by:

$$F = evB = \frac{\gamma m v^2}{\rho} \tag{1}$$

$$B\rho = \frac{\gamma m v}{e} = \frac{E}{ce} \tag{2}$$

The angle of the *kick* can be described by:

$$\theta = \frac{1}{B\rho} \cdot \oint B \, ds = \frac{1}{B\rho} \cdot 2\mu_0 N I h \tag{3}$$

where N is the number of turns of coil, I the current in the coils and h is the size of the vacuum chamber. Therefore the *kick* can be expressed as a linear function of the current:

$$\theta = \frac{ce}{E} \cdot 2\mu_0 N I h \tag{4}$$

In a given accelerator where energy and magnet properties are known, this can be reduced to:

$$\theta[rad] = calconst \cdot I[A] \tag{5}$$

This calibration allows comparison of the model with the measured tune-shift resulting from a corrector kick. Figure 5 shows the theoretically resulting tune-shift from various (horizontal) kicks. As expected the dependency is parabolic. Using the above mentioned conversion scheme (from a current in A to a kick in rad on a corrector magnet) one can now look at measured tune-shift vs. kick on a (horizontal) corrector magnet. This is done in figure 6.

Figure 7 shows a comparison between the model and the measured tune-shifts. One can see easily that the curves have the same shape, but a different slope, which is very bothering. The slope, i.e. the first derivative results from the sextupole terms, so an obvious idea would be to change the sextupole strength until the slopes are equal. This is basically an experimental check of the assumed value of sextupole strength. Another idea is to find a new calibration constant (see equation 5) for the conversion in the corrector magnets. It is possible, that due to inaccuracies in magnetic field measurement the original calibration constants were wrong. Both ideas were pursued and the results will be presented in the next two sections.

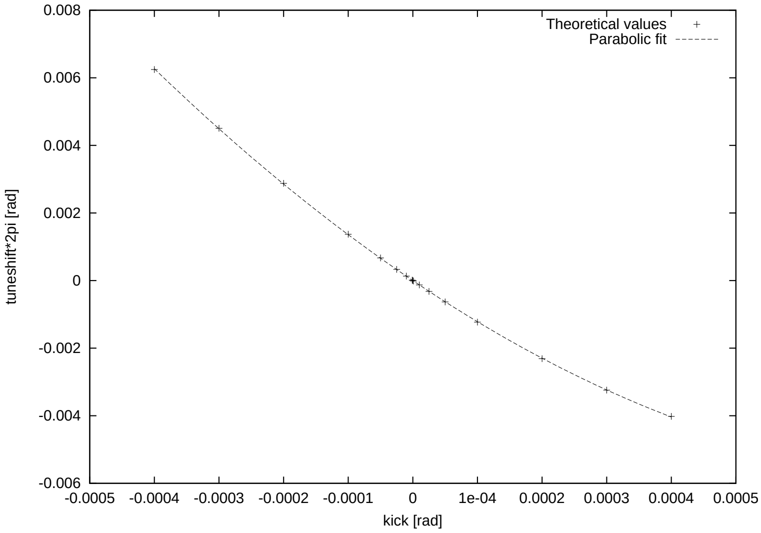

Figure 5: Theoretical prediction of resulting horizontal tune-shifts for different horizontal corrector magnet kicks.

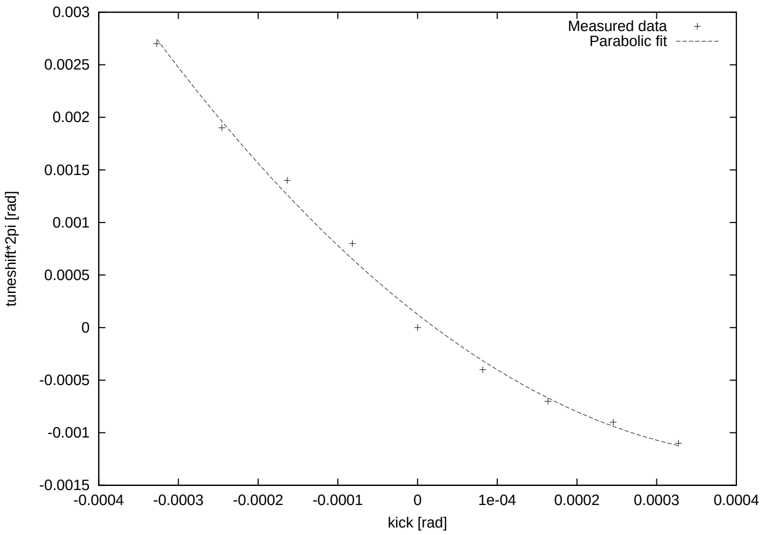

Figure 6: Measured values of resulting horizontal tune-shifts for different horizontal corrector magnets kicks.

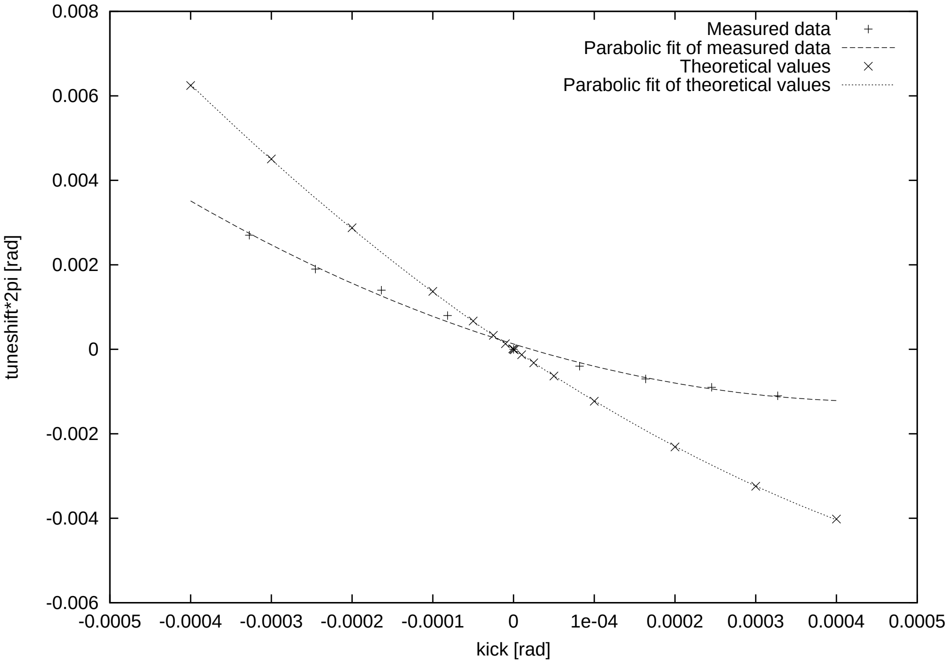

Figure 7: Comparison between the theoretical and the measured tune-shifts.

4.1 Varying Sextupole Strength

As stated above, the first derivative corresponds to the sextupole terms and so the first approach is to reduce the sextupole magnet strength in order to reduce the slope of the parabola until data and theoretical values match. If applicable this procedure can be used to obtain new and more precise values of the sextupole strength. Figure 8 shows a comparison between the original 100% strength and the reduced 90% strength sextupoles. One sees clearly that the slope of the parabola is reduced. Unfortunately this reduction is not sufficient to match theoretical hypothesis with our data (see figure 9). Another attempt to match both is presented in figure 10: After reducing sextupole strength by 50% (!) we achieve a satisfactory match in the region of zero perturbation; but nevertheless, further away from this point the slopes are very different. Even taking into account that magnetic field measurement is not completely precise, it has a higher confidence level than the 50% sextupole strength error would allow. Therefore this procedure of finding a new value for the sextupole strength has to be given up in favor of finding the error in the calibration factor.

4.2 Correcting the Calibration Constant

The other idea mentioned was to find a new calibration constant which would, on one hand, match the measured data to the theoretical predictions and, on the other

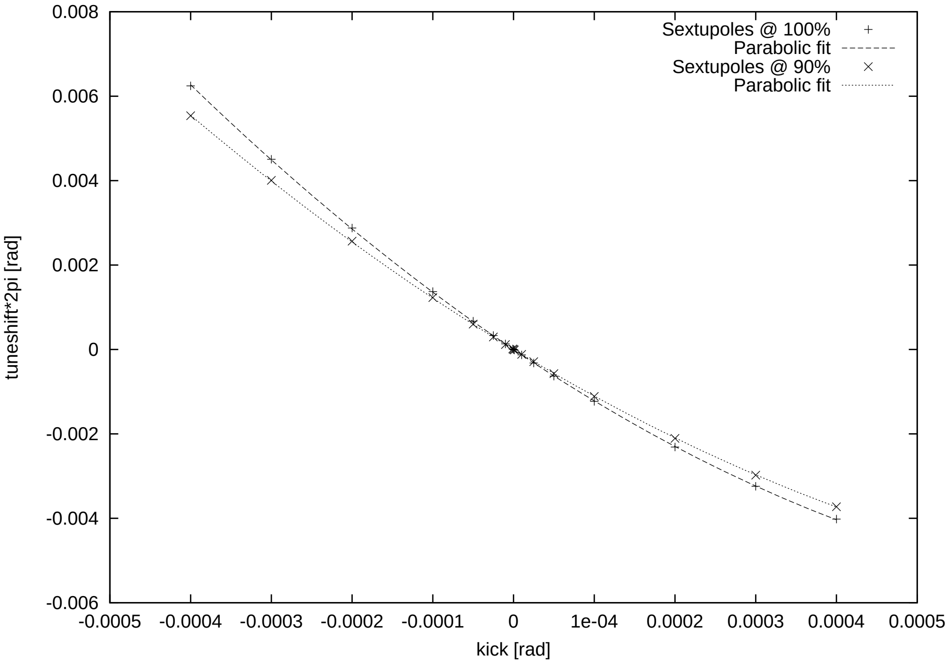

Figure 8: Comparison (theoretical prediction) between the original and reduced sextupole strengths.

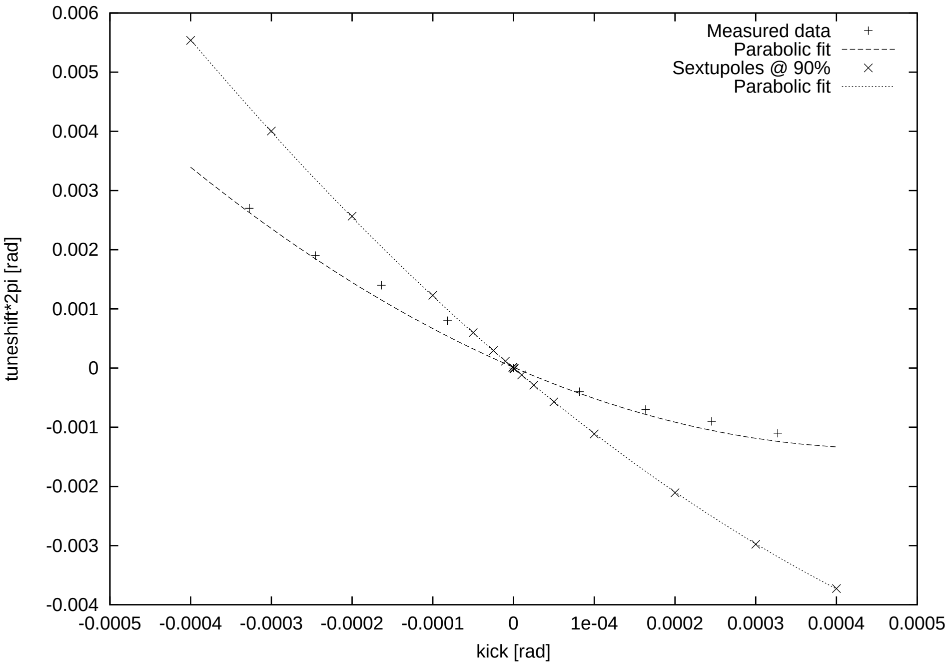

Figure 9: Comparison between the theoretical (90% reduced sextupoles) and measured tune-shifts.

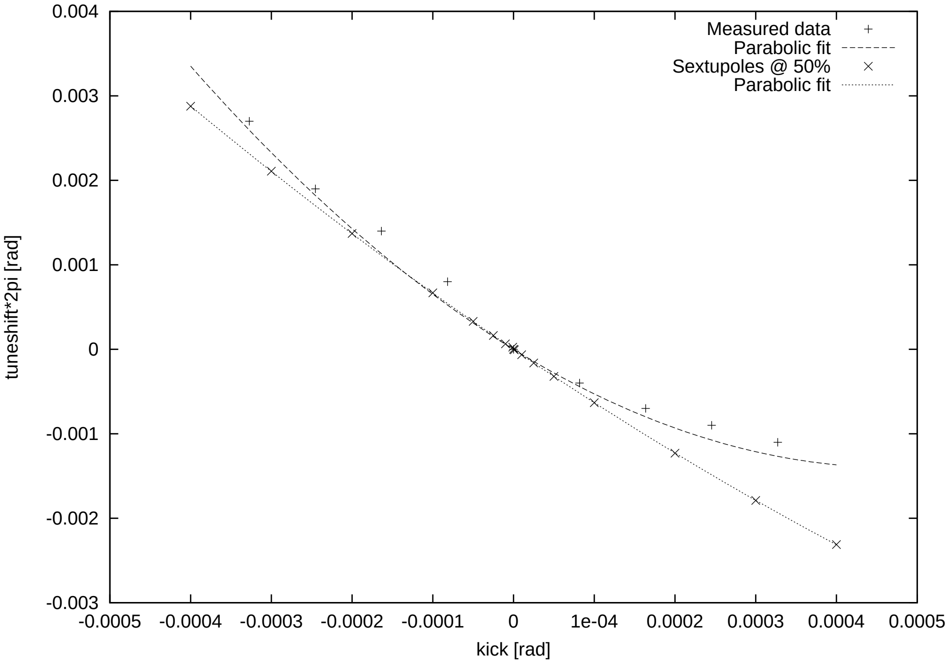

Figure 10: Comparison between the theoretical (50% reduced sextupoles) and the measured tune-shifts.

hand, give us new understandings of the corrector magnets, i.e. correct values of the properties that lead to the calibration constant (e.g. number of turns of coil, current, dimensions of the vacuum chamber, etc.). The implementation is fairly simple: The measured data is plotted again, but under the assumption that the used calibration factor is not known accurately. Assume that the measured tune-shift is exact and find what kick a certain measured tune-shift corresponds to. This leads to several values for the calibration constant. These different values can then be plotted against each other and if they are close enough the mean value gives you an an idea of the realistic calibration constant. Figure 11 shows the calculated calibration constants with respect to the original constant (which was assumed wrong). The mean value of the calculated values is plotted as well.

Even if one uses the calculated mean value as the calibration constant and compares the predicted theoretical values with the measured and converted values, there is no obvious match (see figure 12). The parabolas meet in the region of zero kick, but their slopes are different as soon as one starts to raise the kick value. Therefore this method of correcting the calibration constant has to be abandoned as well.

Up to now, no satisfying explanation for the deviation of experimentally acquired tune-shifts from the theoretically predicted values could be found. The investigation of this question will continue. Unfortunately the calculated values are very far apart from each other which of course lets doubt arise if building the mean really leads to a realistic value. Even worse — the mean value of the calcu-

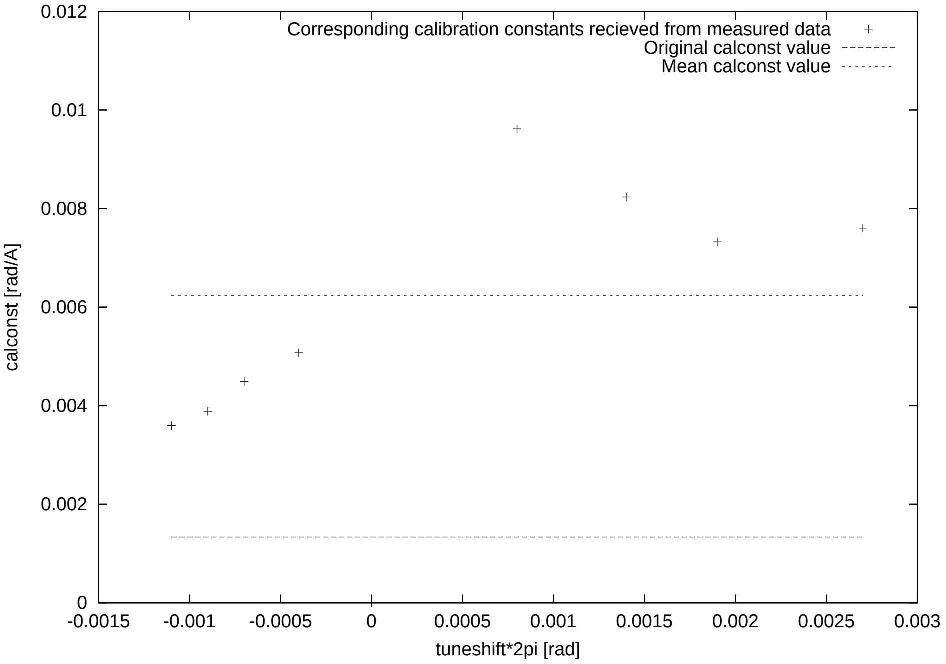

Figure 11: Calculated calibration constants corresponding to measured tune-shifts.

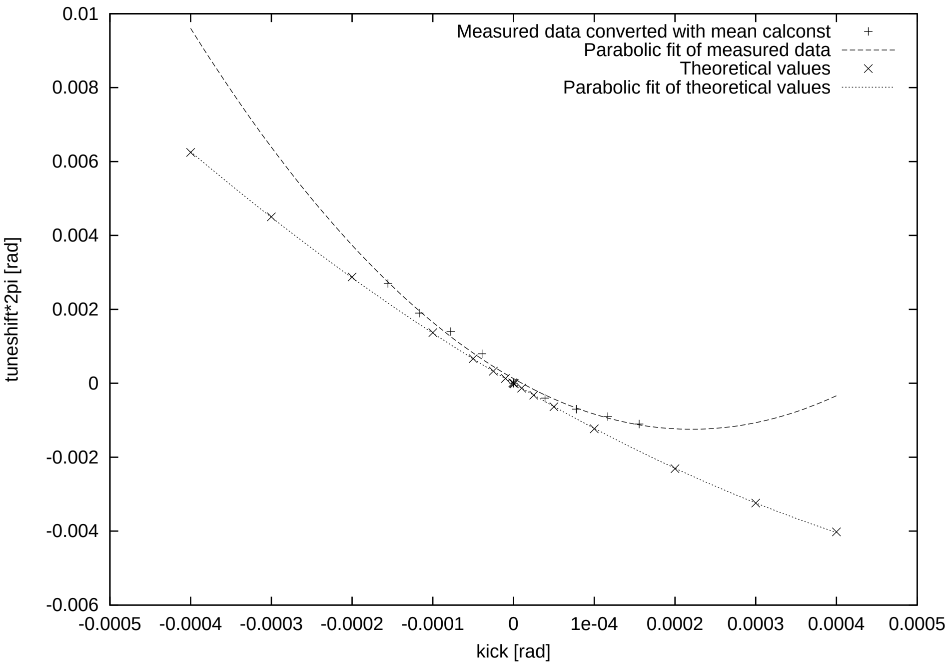

Figure 12: Calculated mean calibration constant used to compare experimental data with theoretical predictions.

lated constants lies at a value about five times greater than expected. Even taking into account that inaccuracies occur during measurement of the magnet properties, there is no possibility of the calibration constant being so high. Cross-checks done by other SLS members using various measurement techniques have proven the estimated factor to not be off by a factor of five.

5 Response Matrix Measurements

5.1 The Response Matrix

The basic idea behind a response matrix measurement is to introduce a small perturbation to the storage ring (i.e. exciting a corrector magnet) and then measure the position of the new closed orbit. In presence of such a kick [4] $x = 0$ or $y = 0$ is now longer a solution. If we look at this kick as a field error we can calculate a new *closed orbit:*

$$x(s) = \frac{\theta\sqrt{\beta(s)\beta_\theta}}{2\sin(\pi Q)}\cos[\phi(s) - \pi Q] \tag{6}$$

where θ is the kick in radians, β_θ is the value of the β-function at the position of the corrector magnet where the kick is applied, Q is the betatron tune, and $\phi(s)$ is the phase advance. Particles will now perform betatron oscillations around this new closed orbit. So basically a response Matrix will result if (after giving a certain kick to each corrector magnet) the orbit displacements are read at various spots along the storage ring, e.g. if we have m corrector magnets and n BPMs then the value $r_{ij}(\theta)$ will represent the displacement of the beam at BPM j induced by corrector i when applying a kick strength θ. So the result of such a response measurement will be the *Response Matrix*

$$R(\theta) = [r(\theta)_{ij}]_{i=1...m,j=1...n}$$

The measurements conducted here are only two column vectors out of such a matrix,

$$\vec{r}_{horizontal} = [r(\theta)_{ik}]_{i=1...m,1\leq k\leq n}$$

$$\vec{r}_{vertikal} = [r(\theta)_{il}]_{i=1...m,1\leq l\leq n}$$

i.e. one corrector (horizontal and vertical) kicks the beam with a certain amplitude and then the response of the beam is measured on all of the 72 BPMs. The experiment consisted of taking data from all of the 72 BPMs after having given once a horizontal kick of +1A on the first horizontal corrector magnet and once a vertical kick of +2A on a vertical corrector magnet. A kick of +1A on a horizontal corrector corresponds to $\theta = -0.1mrad$ whereas a kick of +2A on a vertical corrector corresponds to $\theta = -0.25mrad$. The result of these kicks can be seen in figures 13 and 14.

To compare the theoretical model with measured data, it is a good idea to divide the position of the particles by the square root of the β-function. Recall equation 6 which will then be transformed to:

$$\frac{x(s)}{\sqrt{\beta(s)}} = \frac{\theta\sqrt{\beta_\theta}}{2\sin(\pi Q)}\cos[\phi(s) - \pi Q] \tag{7}$$

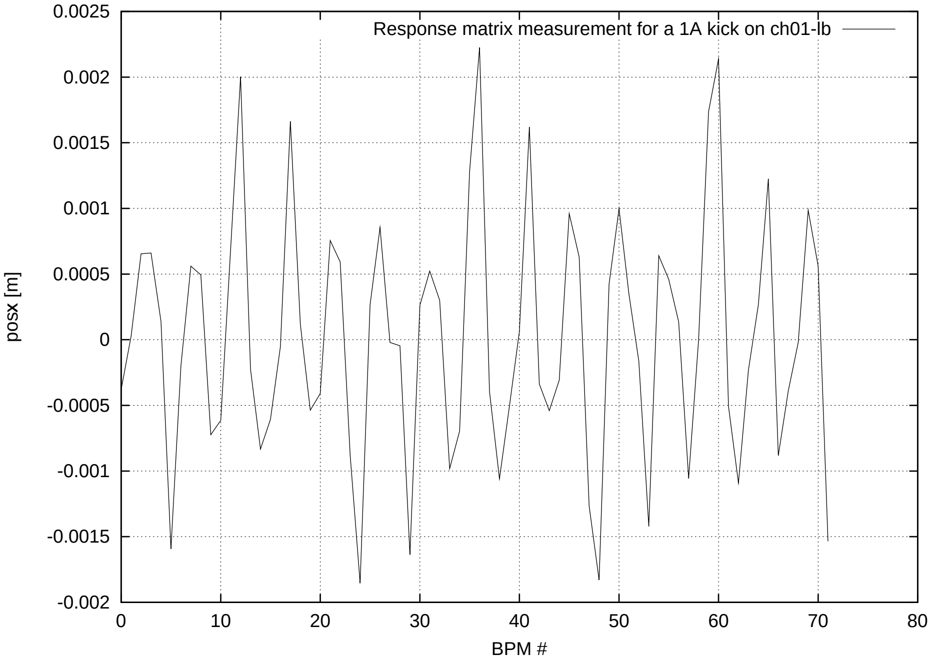

Figure 13: Response Matrix measurement for a kick on a horizontal corrector.

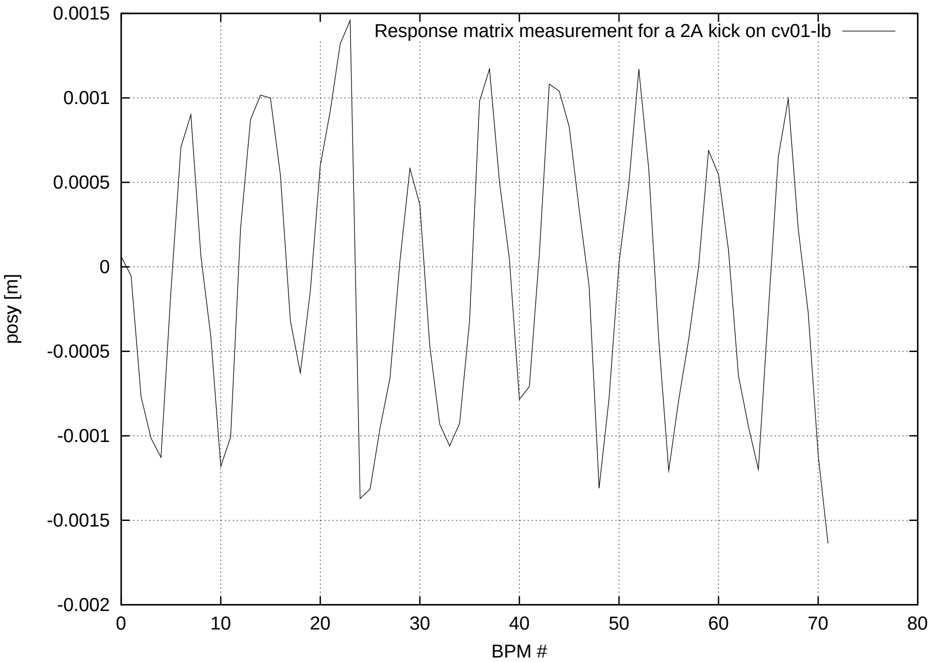

Figure 14: Response Matrix measurement for a kick on a vertical corrector.

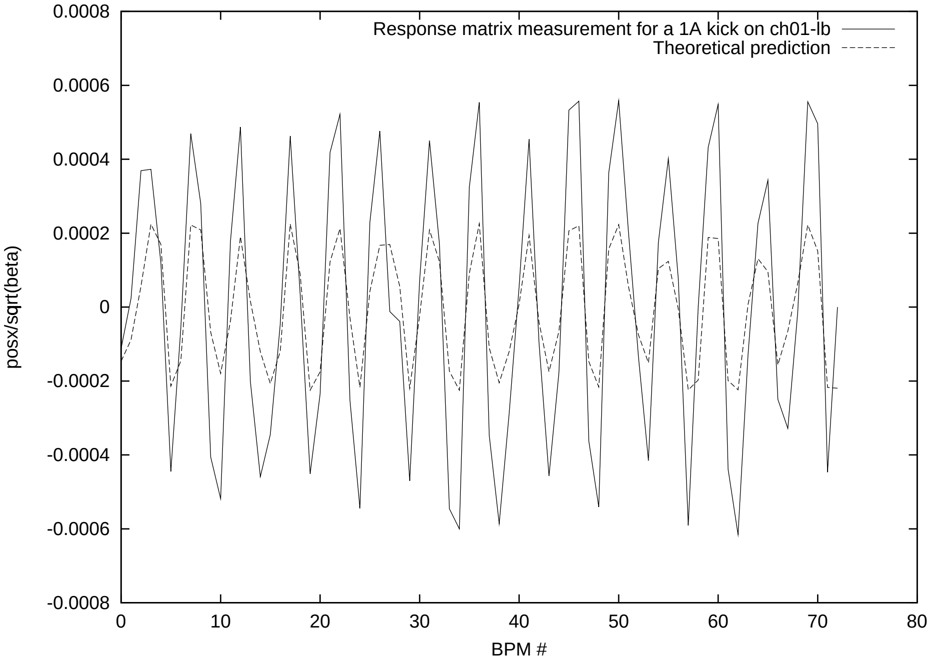

Figure 15: Comparison of results of equation 7 for a horizontal kick between measured data and theoretical prediction.

All factors outside the cosine are constant and so using equation 7 we can study the form of the cosine with respect to the phase advance $\phi(s)$. A comparison of these values (see figures 15 and 16) shows that the phase is well predicted by theory (the tunes differ by less than a half-integer).

If we want to compare the amplitudes of these values it is better to look at their difference as in figures 17 and 18. However it is important to keep in mind that there is also a resolution problem: There are only 72 BPMs even though the beam position is oscillating very quickly, so that readings may look offset even though they are in good agreement with theory; this can be seen in figures 15 and 16.
Figures 17 and 18 show a modulation of the beam position amplitudes over the period of the storage ring. This comes from the so-called *beta-beat* which can be derived from these plots.

5.2 The Beta-Beat

If one assumes that the beam position of the theoretical calculation and the measurements have to lie over each other and the tune, the phase and the kick are measured correctly, then a difference between theoretically predicted and measured β-function (i.e. the beta-beat) can be calculated. Taking equation 6 one receives:

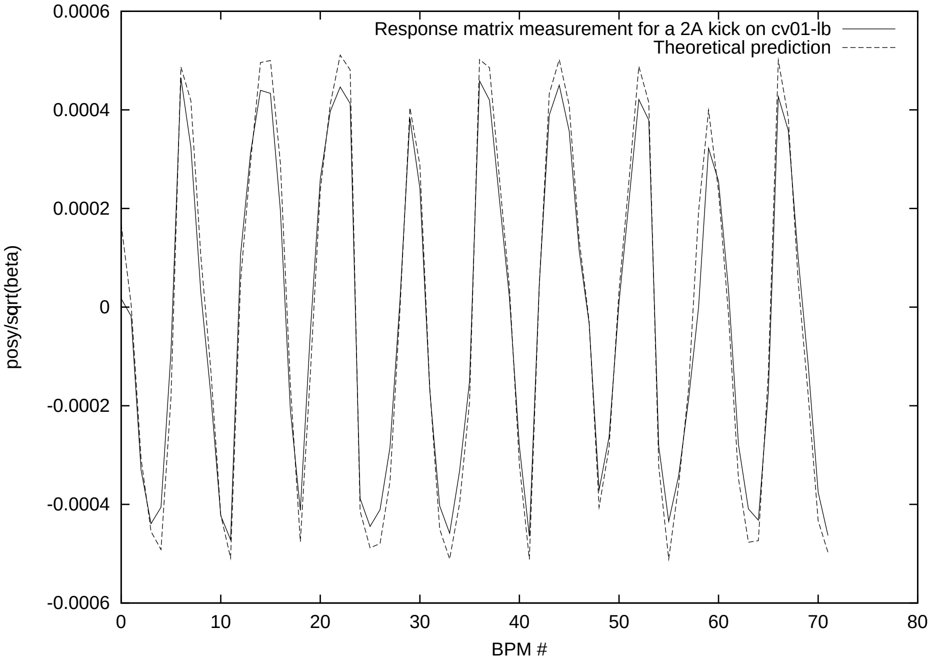

Figure 16: Comparison of results of equation 7 for a vertical kick between measured data and theoretical prediction.

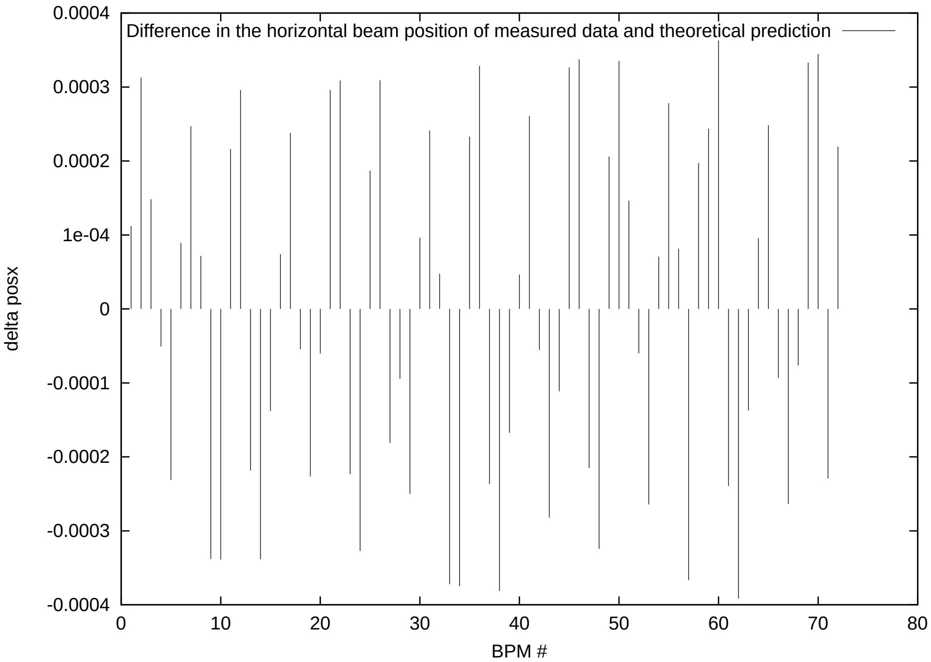

Figure 17: Comparison of the amplitudes of measured data and theoretical prediction for a horizontal kick.

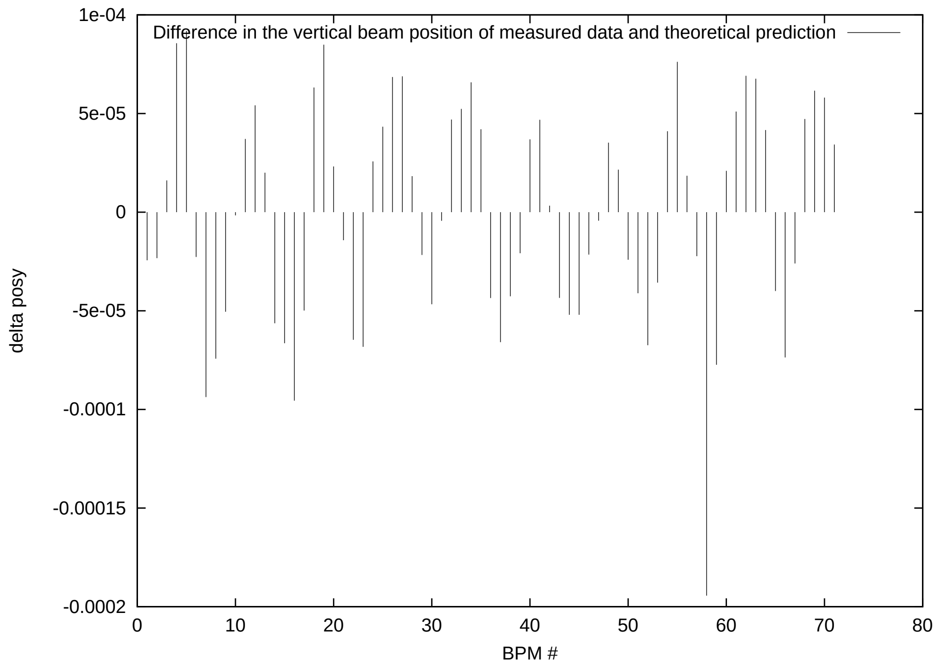

Figure 18: Comparison of the amplitudes of measured data and theoretical prediction for a vertical kick.

$$\frac{x_{theory}(s)}{x_{data}(s)} = \sqrt{\frac{\beta_{theory}(s)}{\beta_{data}(s)}} \tag{8}$$

And this then leads to a value for the actual β-function of the storage ring at any given position s:

$$\beta(s) = \beta_{theory}(s) \cdot \left(\frac{x_{data}(s)}{x_{theory}(s)}\right)^2 \tag{9}$$

A plot of this actual β-function compared to the theoretical β-function is given in figure 19.

Another interesting discovery are the two spikes at BPM 28 (bpm_05sd) and BPM 59 (bpm_10me). It turned out that BPM 59 (bpm_10me) was turned off during measurement (because of a malfunction) and BPM 28 (bpm_05sd) was giving the wrong readout due to insufficient settings. As a consequence of this measurement these errors were corrected.

5.3 Varying the Calibration Constant and the Tune

As already mentioned, the amplitudes of theoretical prediction and of data do not match perfectly. Aside from the modulation of their difference due to beta-beat,

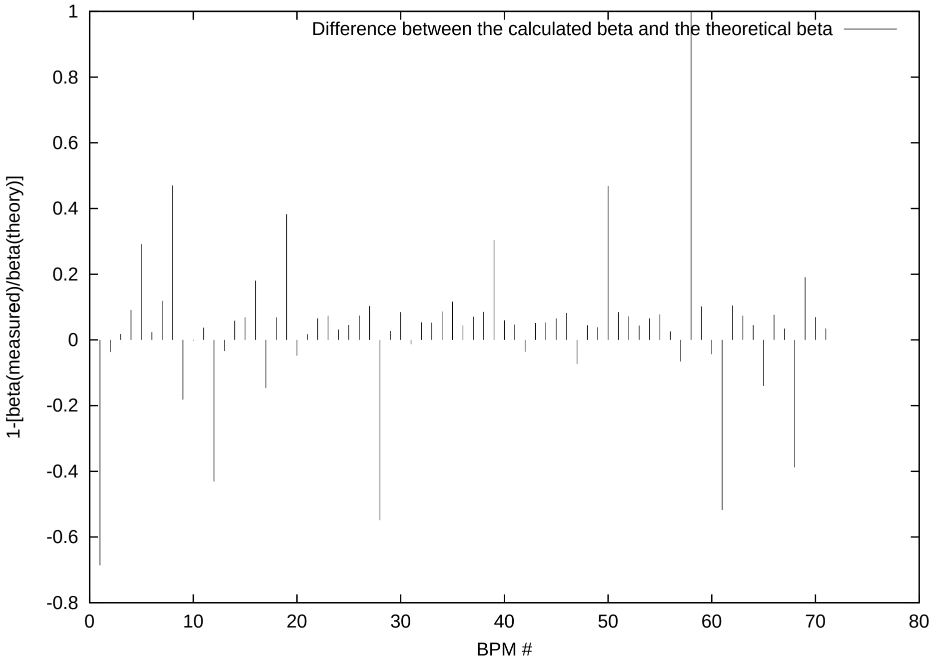

Figure 19: Comparison of the β-functions of measured data with theoretical prediction.

there seems to be a threshold in difference. This again leads to the assumption that under circumstances the calibration factor of the corrector magnets was not evaluated correctly. Figure 20 shows minimization of the difference between theoretical predictions and measured values after changing the horizontal calibration constant:

$$calconst_{horizontal} : 8.5 \cdot 10^{-3} \longrightarrow 16.6 \cdot 10^{-3}$$

This leads to a minimized difference of the two plots (their difference has a mean of $3 \cdot 10^{-6}$ and a RMS of $1.5 \cdot 10^{-4}$), but it doesn't give us any proof considering the properties of our corrector magnets. Once again the calibration constant would have to be changed by a great factor which at the moment cannot be legitimated. The fact that the difference between the two calibration constants is almost exactly a factor two is even more bothering.

There is however another possible approach: Perhaps the β-function used by the Tracy code is not identical to the actual β-function when we took experimental data. Recall that in equation 6 the phase and the β-function depend on each other as a result of solving Hill's equation [4]:

$$\phi(s) = \int_0^s \frac{d\overline{s}}{\beta(\overline{s})} \tag{10}$$

Therefore a beta-beat will have influence on the phase. This influence may be only

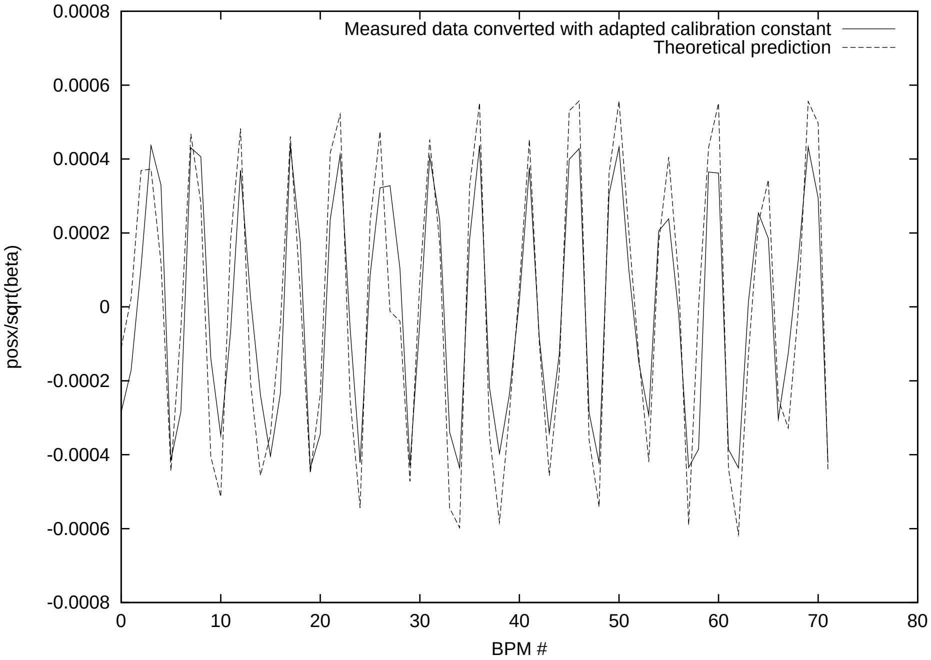

Figure 20: Comparison of the amplitudes of measured data (with adapted calibration constant) and theoretical prediction. Their difference has a mean of $3 \cdot 10^{-6}$ and a RMS of $1.5 \cdot 10^{-4}$.

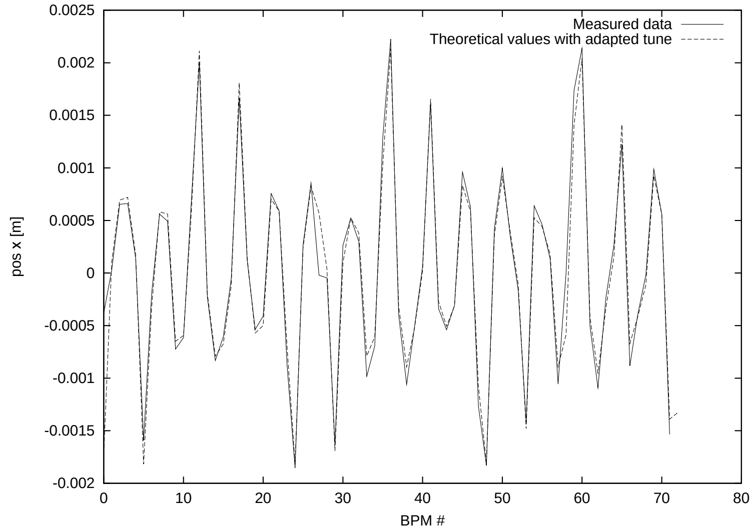

Figure 21: Nicely matching horizontal beam positions after adapting the Tracy tune value. The difference between measured data and theoretical values has a mean of $1.5 \cdot 10^{-5}$ and a RMS of $2 \cdot 10^{-4}$.

small because of the inverse relationship but nevertheless it should be taken into account. Of course if the phase is shifted by only a small deviation this will have great consequences for the BPM readings because their position (in reference to phase advance) is shifted. Even if this shift is small, the position readings may be completely off because of the strong oscillation of the beam position around reference orbit.

Thus the Tracy code was modified to include the possibility of tune adjustment (by quadrupole magnets). The vertical beam positions were in good agreement with theoretically calculated values, but horizontal positions were way off. Therefore the horizontal tune was adjusted in the Tracy evaluation until good agreement between experimental data and theoretical values was achieved. The result is shown in figure 21 (the difference between measured data and theoretical values has a mean of $1.5 \cdot 10^{-5}$ and a RMS of $2 \cdot 10^{-4}$). The corresponding tune values were (tune in vertical direction left unchanged):

$$Q_x = 15.1$$
$$Q_y = 9.6$$

So this method basically illustrates a way of tune measurement. We can now be assured that the tune of the storage ring (while we took experimental data) was at the values $Q_{x,y}$ stated above.

6 Acknowledgements

I would like to thank Michael Boege and Lenny Rivkin for their generous effort to teach me so much about accelerator physics and their kind supervision. Even when they were under great workload they always took time to give me additional advice. I am greatful to Jan Chrin for his explanations about the Corba environment and the software used in the beam dynamics group as well as to Andreas Luedecke for his explications concerning technical aspects of the accelerator. Finally, I thank the whole team at SLS for these very interesting weeks, their valuable information and their kind and encouraging climate. I have learned much and experienced many great hours here at SLS.

References

[1] Michael Boege et al.: *The Swiss Light Source Accelerator Complex: An Overview*, 6th EPAC Proceedings, Stockholm, August 1998

[2] Johan Bengtsson: *Tracy-2 User's Manual*, Incomplete Draft

[3] J. Safranek: *Experimental determination of storage ring optics using orbit response measurements*, NIMPR, A 388 (1997) 27-36

[4] Lenny Rivkin: *Physics of Particle Accelerators*, Lecture notes, Lecture given at ETH, Summer Semster 2000

[5] Etienne Forest: *Beam Dynamics: A New Attitude and Framework*, Harwood Academic Publishers, Amsterdam, The Netherlands, 1997