Beam-based Calibration of the Linear Optics Model of ELSA

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Abstract

The Electron Stretcher Accelerator (ELSA) of Bonn University is used to provide an external electron beam of high duty factor in the energy range from 0.5–3.5 GeV for fixed target experiments. In the near future polarized electron beams will be accelerated up to the highest energies. In order to avoid depolarization of the beam by imperfection and intrinsic resonances the control of the closed orbit and the symmetry of the ring lattice has to be improved. For calibration of the optics model of ELSA the orbit response matrix has been measured and fitted with help of the program CALIF. The strengths of the two quadrupole families and the relative scaling factors for the beam position monitors and corrector magnets have been determined this way. The results of the fits and a comparison with measurements of the optical functions of ELSA will be presented.

1 INTRODUCTION

Since 1987 Bonn University operates the **El**ectron **S**tretcher **A**ccelerator ELSA [1] which is used to deliver a nearly continuous electron beam to three fixed target experiments in the energy range between 0.5 GeV and 3.5 GeV. The accelerator facility consists of two LINACs equipped with polarized and unpolarized electron guns, a rapid cycling booster synchrotron (50 Hz) and the main ring ELSA (fig. 1). Using a third integer resonance the pulses injected from the booster into ELSA are slowly extracted for a duration of up to a minute and delivered to one of three external experiments.

To some extend ELSA is used as a partially dedicated light source. Currents of more than 250 mA can be stored in ELSA at 1.6 GeV and lifetimes of up to 3 hours for 15 mA at 2.3 GeV have been achieved, which are merely vacuum limited.

The ELSA lattice was designed with a two-fold symmetry and is composed of 16 FODO cells build up in two arcs and two straight sections. Integrated into the arcs are missing-magnet dispersion suppressors to provide vanishing dispersion in the straight sections containing the injection magnets, RF cavities and sextupoles used for the resonance extraction. Besides the two quadrupole families there are four sextupoles for chromaticity correction per plane and four sextupoles to drive the third integer resonance used for extraction.

One of the main goals in the future will be the acceleration of a polarized electron beam up to an energy of 3.5 GeV. In order to avoid the depolarization due to imperfection and intrinsic resonances, correction methods (harmonic correction and tune jumping) have to be applied [6].
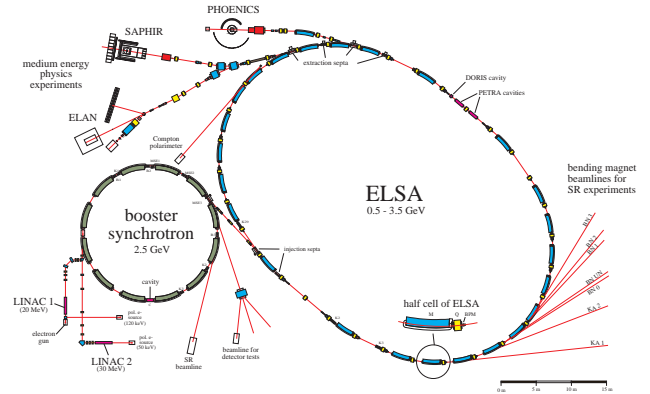

Figure 1: Layout of the facility ELSA

For an appropriate correction a better knowledge of the optics is necessary, because some of the depolarizing resonances are suppressed due to the supersymmetry of the lattice. This symmetry is broken by gradient errors and by a nonzero orbit in the sextupole magnets.

The calibration of the internal polarimeter of ELSA will be done by using the self-polarization of the beam. The appearence of reasonable polarization depends strongly on the control of the closed orbit in the quadrupoles. We will adopt the method of k-modulation of single quadrupoles [5] to center the beam in the quadrupoles and to find the offset between the center of the BPM and the magnetic center of the nearby quadrupole. For the reconstruction of the position of the beam in the quadrupoles the exact knowledge of the optics is mandatory.

2 THEORY

The method of beam-based calibration of the optics model uses the analysis of the measured orbit response matrix $\bar{\mathbf{C}}$ [2] [4]. The elements of the response matrix

$$\bar{\mathbf{C}}_{ij} = \frac{\Delta x_i}{\Delta \theta_j} \tag{1}$$

are defined as the change of the beam position Δx_i at the beam position monitor (BPM) i due to a change of the kick $\Delta \theta_j$ of the corrector magnet j.

The theoretical response matrix $\mathbf{C}$ is expanded to first order in the fit parameters (for instance the gradients of single quadrupoles k_l) using an accelerator modeling program. Each matrix element $\bar{\mathbf{C}}_{ij}$ depends on the BPM gain x_i and the corrector scale factor y_j. This results in the fol-

lowing equation:

$$x_i \bar{\mathbf{C}}_{ij} \, y_j = \mathbf{C}_{ij} + \sum_l \frac{\partial \mathbf{C}_{ij}}{\partial k_l} \delta k_l \quad . \qquad (2)$$

For the solution of this least-square problem it has to be taken into account, that for each plane all BPM gain factors x_i can be increased when all corrector scaling factors y_j are reduced at the same time and vice versa. In the computer program CALIF [2], which we used for the analysis of the measured orbit response matrix $\bar{\mathbf{C}}$, two methods are implemented to deal with this degeneracy of the problem.

The first one uses an alternating fitting of the BPM gains x_i in combination with the focusing strengths k_l and the corrector scalings y_j in combination with the k_l.

The other method is to solve the linear equation system for the fit parameters and to remove the degeneracy of the problem by using the singular value decomposition[3]. In addition this fit considers, that a kick $\Delta \theta_i$ of a corrector at a place with non-vanishing dispersion D_x leads to an energy change of

$$\frac{\Delta E}{E} = \frac{\Delta \theta_i D_x}{\alpha C_0} \qquad (3)$$

in a machine with momentum compaction factor α and circumference C_0, which effects the measured data of all BPMs.

3   MEASUREMENTS

For the closed orbit correction of ELSA, 24 BPMs (both planes), 16 horizontal and 17 vertical corrector magnets are available. Therefore the orbit response matrix $\mathbf{C}$ has $48 \times (16 + 17) = 1584$ matrix elements, which can be used for fitting the optics model and the BPM and corrector scaling factors.

In order to reduce the number of fit parameters of the optics model all chromatic and extraction sextupoles were turned off. Otherwise additional focusing and defocusing fields emerging from the nonzero orbit in these nonlinear elements would appear.

The measurement of the response matrix was done automatically and took about one hour. The current change was equal for all corrector magnets and created closed orbit deviations with peak amplitudes of several millimeters.

4   ANALYSIS

The measured response matrix was then analyzed with the help of the computer code CALIF. The set of the 48 BPM gain factors x_i, the 33 scaling factors of the corrector magnets y_j and the two quadrupole strengths k_l of the main quadrupole families were chosen as fit parameters.

We used both methods implemented in CALIF to deal with the degeneracy of the BPM/corrector scaling problem. Both methods converged to nearly the same solution. The corrector scale factors y_j were fitted with an relative error of ≈ 1.4 % and the BPM gains x_i with ≈ 2 %. For the rms resolution of the BPMs we found values between 200
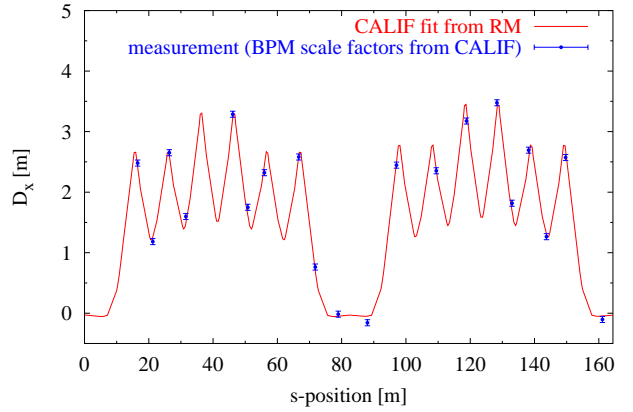

Figure 2: Measurement of the horizontal dispersion function (the BPM data were scaled with the gain factors obtained from the CALIF fit) and prediction from the fitted optics model
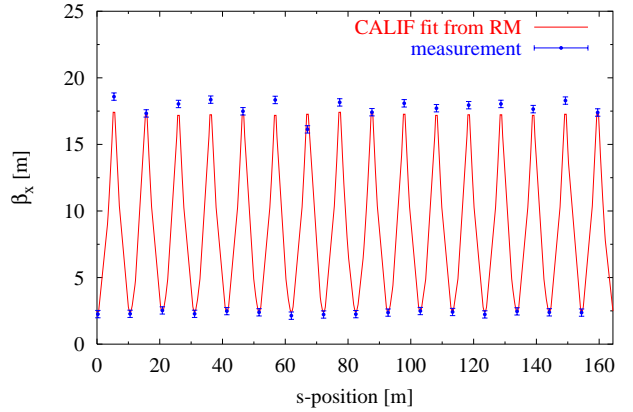

Figure 3: Measurement of the horizontal beta function and prediction from the fitted optics model for the ELSA lattice
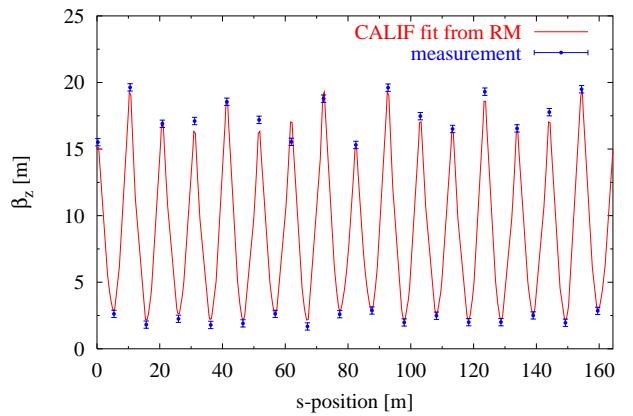

Figure 4: Measurement of the vertical beta function and prediction from the fitted optics model for the ELSA lattice

and 300 μm, which are in good agreement to our previous experiences with the BPM system.

At first we checked whether the fit reconstructed the right scaling factors of the two different types of corrector magnets in use at ELSA. In places with less space a shorter version of the corrector with about 70 % field strength had been installed. CALIF successfully found all these correctors and was also able to find the three magnets with interchanged polarity (a fact which was already known).

In order to decide if the fit converged to the right solution, predictions from the optics model have to be compared with independently measured data. One such value is the tune of the machine, because in no place it entered into the analysis of the response matrix. We found that the tunes agreed very well with the tunes computed from the model. The differences between the measured and the computed tune from the model were $\Delta Q_x = 0.002$ in the horizontal and $\Delta Q_z = -0.001$ in the vertical plane.

Other parameters, which can be checked, are the optical functions of the machine. The dispersion function can be calculated from the well known expression

$$D_x = -\alpha \Delta x \frac{f_{\mathrm{RF}}}{\Delta f_{\mathrm{RF}}} \quad , \qquad (4)$$

by measuring the displacement of the beam Δx due to the change in the RF frequency f_{RF}.

In figure 2 the dispersion function predicted from the fitted optics model and the measured data are plotted. The measured data were rescaled with the BPM gain factors obtained from the fit. The measured data without this rescaling had deviations of several ten percent from the theoretical values.

The beta functions were measured by k-modulation of the 32 quadrupoles. For the purpose of the precise measurement of the position of the BPMs with respect to the magnetic center of the nearby quadrupoles we installed a k-modulation system [5], which allows to change the focusing strength of a single quadrupole of up to $\Delta k / k = \pm 1$ % using an additional power supply. From the tune shift ΔQ and the effective magnetic field length l_{eff} the mean beta function

$$\bar{\beta} = \frac{4\pi \Delta Q}{\Delta k \, l_{\mathrm{eff}}} \qquad (5)$$

in the quadrupole can be calculated.

The measured data and the prediction from the fitted optics model for the beta functions are shown in figures 3 and 4. As we fitted only the strength of the quadrupole families, it is not possible to model effects like the beating of the beta functions evoked from gradient errors of single quadrupoles.

The fit of the measured response matrix predicted that the quadrupole strengths have to be increased by 2.9 ‰ for the F-quadrupoles and 0.4 ‰ for the D-quadrupoles in contrast to our current theoretical model of ELSA. Thereupon we investigated the quadrupole power supplies and found that this deviation was partially caused by a faulty balancing in one of the power supplies and a DAC scaling error.

We also tried to include the strengths of the 32 single quadrupoles in the set of fit parameters. Unfortunately, this fit failed and pairs of quadrupoles with strength deviations of nearly equal size but reversed signs showed up. The probable reason for this behaviour is the unequal distribution of the corrector magnets due to lack of space along the circumference of ELSA, leading to quadrupole pairs with no corrector in between.

5 CONCLUSIONS AND PLANS

With the analysis of the measured response matrix it was possible to fit the two quadrupole families of ELSA and the BPM and corrector scale factors. The tunes calculated from the model fit closely to the measured values. Also the optical functions are in good agreement with the measured data. We were able to determine the gain factors of the BPMs and found some faulty hardware.

In the future we plan to increase the number of correctors to allow also the measurement of single quadrupole gradient errors, which we were not able to fit so far. The old BPM system will be substituted by a new one with a much higher resolution, offering to fit also for other parameters like the s-positions or the tilts of the elements.

6 ACKNOWLEDGEMENTS

7 REFERENCES

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