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HIGH BANDWIDTH CLOSED ORBIT CONTROL FOR A FAST RAMPING ELECTRON ACCELERATOR*

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Abstract

ELSA is a fast ramping stretcher ring capable of acceleration and storage of polarized electrons with energies up to 3.2 GeV. To preserve the initial degree of polarization, the acceleration is performed by a fast energy ramp with a maximum ramping speed of 6 GeV/s. During acceleration especially the vertical orbit needs to be continuously corrected so that the vertical rms deviation does not exceed 50 μm at any time. In order to compensate the so called integer resonances, which occur at certain energies, the orbit correction system further needs to provide additional, empirically determined, harmonic field distributions. A successful application of these combined correction measures requires a considerably high bandwidth of up to some 100 Hz. In our contribution we will have a closer look at the performance and the acquired bandwidth of the correction system.

OPTIMIZATION OF POLARIZATION

At ELSA, polarized electrons are generated in an dedicated source for polarized electrons. After pre-acceleration in a fast booster synchrotron these are injected into the ELSA stretcher ring at 1.2 GeV. At injection the degree of polarization is approximately 72%. However, during the following post acceleration stage[1] the so called *integer spin tune resonances* have to be compensated: During acceleration, every 440 MeV the spin tune $a\gamma(t)$ becomes an integer and the spin precesses in phase with the particle's revolution. Horizontal magnetic field components periodically acting with the spin precession frequency will then lead to depolarization. Without compensation the remaining degree of polarization after the acceleration would be lower than 40 % [1].

At ELSA we use a harmonic correction scheme. Since the driving horizontal field distributions are unknown, an empirical approach is inevitable: Additional harmonic kick distributions varying sinusoidally $a\gamma$ times along one revolution are applied every 440 MeV during acceleration. These additional kicks have to be applied in such a way that they cancel the unwanted driving harmonic fields. Amplitude and phase of these distributions have to be found empirically for every resonance by iteratively optimizing the final degree of polarization.

In order to apply the compensating horizontal magnetic fields, the vertical closed orbit correction system is used: Based on a precisely corrected vertical closed orbit (average rms value below 50 μm) additional vertical steerer magnet kicks are added. These will cause further vertical orbit displacements in the quadrupole magnets, leading to additional vertical kicks. It is rather unlikely that the combination of these two effects will produce the wanted harmonic distribution. To calculate appropriate kicks we use a measured orbit response matrix and an algorithm that is implemented as explained in [2]. The linear algebra part of the algorithm is carried out by the open source C++ library *armadillo* [3]. Thereby the calculated distribution of the corrector kicks itself is not necessarily harmonic anymore.

In addition the vertical corrector system must be capable of changing corrector kicks between two integer spin tune resonances. At our maximum acceleration speed of 6 GeV/s this leads to a minimal time between two resonances of

$$\Delta t_{\text{imp}} = \frac{440\ \text{MeV}}{6\ \text{GeV}} \approx 73\ \text{ms} \tag{1}$$

THE ORBIT CORRECTION SYSTEM

Each of ELSA's 32 quadrupole magnets is equipped with an in-house developed four-button beam position monitor (BPM) chamber [4]. These are mechanically fixed to the geometric center of the magnets with a precision of ± 0.2 mm. The remaining position offsets are measured by beam based alignment techniques and are then removed by software calibration.

For closed orbit correction in the vertical plane an optimized C-shape magnet design was developed. Together with in-house developed programmable four-quadrant power supplies this system has a slew rate greater than 760 A/s while driving the magnet coil.[2] [5]

Figure 1 gives an overview of the closed orbit correction setup at ELSA. In the following sections we will have a closer look at the bandwidth of the subsystems and we will give an approximation of the bandwidth of the orbit correction.

Table 1: Characteristics of the Vertical Steering Magnets

voltage	200	V
inductance	260	mH
field integral	**9.8**	mT m
field reversal time	**20**	ms
weight	30	kg
dimensions	25x30x15	cm^3
max. current	8.0	A
max. field	40	mT
max. kick(@ 1 GeV)	2.3	mrad
max. kick(@ 3.2 GeV)	0.84	mrad

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[1] Another prominent type are so called intrinsic resonances. These originate out of the single particle motion and strongly depend on the vertical betatron oscillation.

[2] The required slew rate for a complete current reversal at a ramping speed of 6 GeV/s is: $\frac{16\ \text{A}}{73\ \text{ms}}$ ≈220 A/ms

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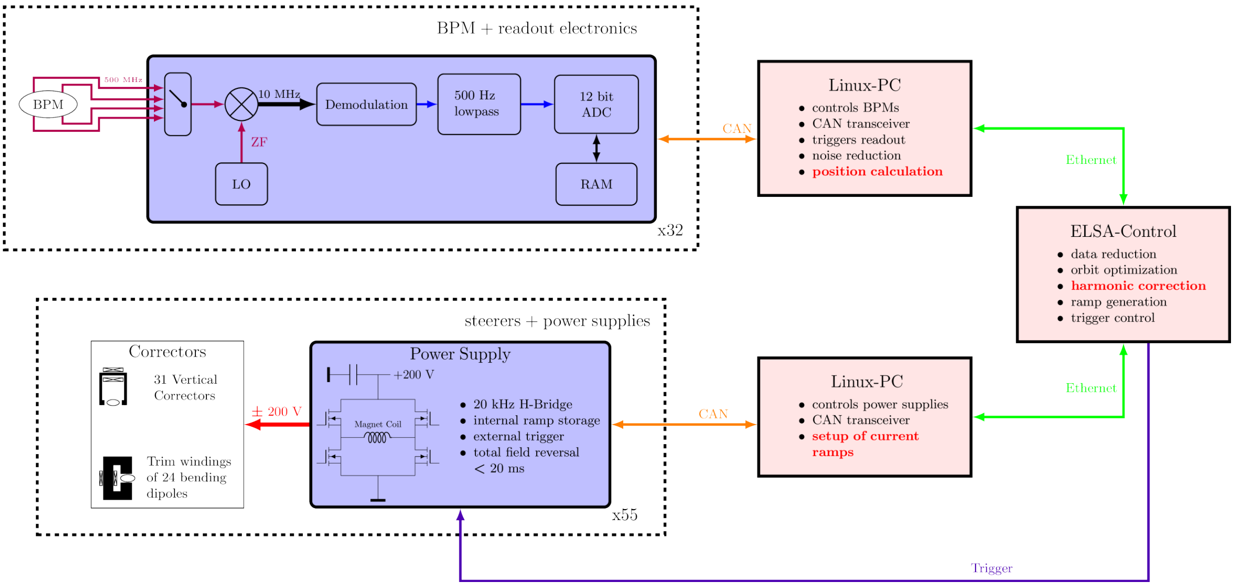

Figure 1: Schematic overview of the closed orbit correction setup. Beam positions are measured and digitized at 32 BPM stations and then transported to the top level accelerator control system. Here, orbit corrections are calculated and applied via 55 programmable power supplies to 31 vertical steerer magnets and 24 extra trim windings at the bending dipoles for horizontal steering [6].

Bandwidth of Beam Position Measurement

Beam position data is stored locally in the readout electronics of each BPM. Up to 4095 data points can be stored. The acquisition rate of the BPM readout stations is limited by their synchronous demodulating device at 1 kHz, thus the development of beam displacement during the first 4 seconds (covering the injection, ramping and a large portion of extraction phase) of the ELSA cycle is available. In order to prevent aliasing, low pass filters are connected in series. According to the Nyquist–Shannon sampling theorem, the maximum allowed filter frequency is $f_{\mathrm{max}} < \frac{1}{2} f_{\mathrm{BPM}}$. The maximum bandwidth of the beam position measurement system therefore amounts to

$$B_{\mathrm{BPM}} = 500\ Hz \tag{2}$$

Bandwidth of the Vertical Steerer Magnets

The bandwidth of the steering system can be determined from measuring the frequency response of a steerer magnet to a sinusoidal varying excitation signal sent to its power supply. When increasing the stimulating frequency, the amplitude of the actual current will decrease. The bandwidth of the system can then be defined as the frequency f_{cutoff} at which the measured amplitude is reduced to $\frac{1}{\sqrt{2}}$. In Fig. 2 the results of such a measurement are shown. Based on this direct method the bandwidth can be determined to

$$B_{\mathrm{steer}} = 205 \pm 2\ \mathrm{Hz} \tag{3}$$

CORRECTION BANDWIDTH

The closed orbit correction bandwidth is the combination of the bandwidth of steering magnets and bandwidth of

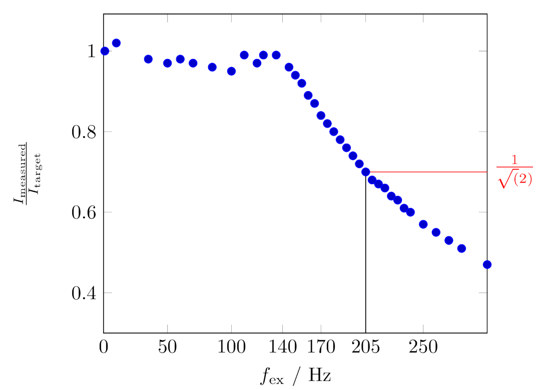

Figure 2: Bandwidth of the vertical steerer magnets: Shown is the ratio of measured to target current through the coil of one steering magnet versus the excitation frequency. The bandwidth is marked at 205 Hz.

orbit response measurements. In order to determine this bandwidth, which is the limiting bandwidth for resonance crossing, we applied two different approaches:

Step Response Analysis: As a rough approximation a steerer magnet can be modeled by a simple RC low pass filter, where the bandwidth can be specified from its step response. The bandwidth of such a system is linked to the 10% – 90% rise time[3] t_{rise} using

[3] For an RC low-pass with $f_{\mathrm{cutoff}} = \frac{1}{2\pi\tau}$ the step response is: $V(t) = V_0\left(1 - e^{-\frac{t}{\tau}}\right)$. The rise time (10% to 90%) then is: $t_{\mathrm{rise}} = t_{90} - t_{10} \Longrightarrow t_{\mathrm{rise}} = \tau \cdot (\ln 0.9 - \ln 0.1)$ which leads to: $f_{\mathrm{cutoff}} = \frac{0.35}{t_{\mathrm{rise}}}$

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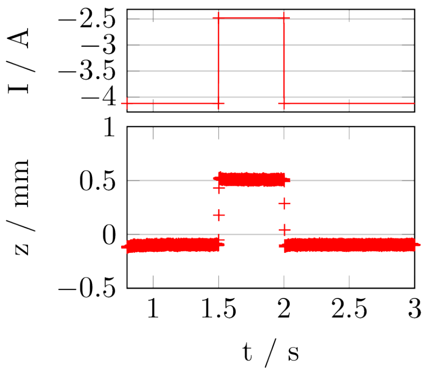

Figure 3: Step response analysis: The top part shows the current through a steering magnet coil while applying a kick step excitation of 1 mrad. In the lower part the corresponding beam position response is shown.

$$B_{\mathrm{RC}} = \frac{0.35}{t_{\mathrm{rise}}} \tag{4}$$

This may be used to convert a measured step response of the closed orbit correction to its corresponding bandwidth. The step response was measured by applying a sudden current step to one steerer magnet. Since we know that the beam position measurement has a much higher bandwidth than the steerer magnets (see equation (2)), we can utilize the monitors for the response measurements. Figure 3 shows the response of the beam position in quadrupole magnet 29 in case of an excitation with a kick step of 1 mrad. A fit of the rise time leads to $t_{\mathrm{rise}} \approx 2.0 \pm 0.1$ ms. Using equation (4) this can be converted to a correction bandwidth of

$$B_{\mathrm{correction}} \approx 175 \pm 8 \text{ Hz} \tag{5}$$

Harmonic Excitation: However, measuring the cutoff frequency provides a direct access to the bandwidth of the orbit correction. This has been carried out by applying a sinusoidal excitation of a single steerer magnet and measuring the amplitude of the closed orbit distortion at that excitation frequency. The cutoff frequency can be determined analog to the analysis of the steering magnet bandwidth (see Fig. 2). In Fig. 4 the results of this method are shown. The correction bandwidth can be determined to

$$B_{\mathrm{correction}} \approx 170 \pm 5 \text{ Hz} \tag{6}$$

The two different approaches give similar results for the correction bandwidth. It is dominated by the bandwidth of the steerer magnets, as one would expect.

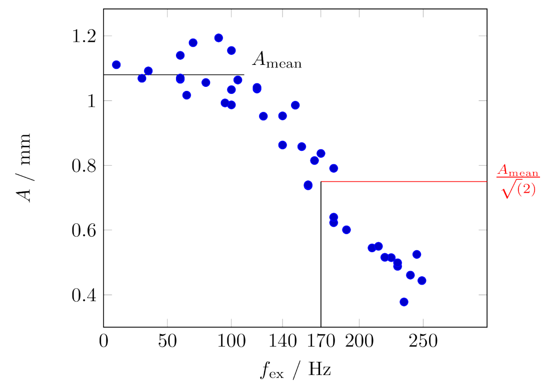

Figure 4: Bandwidth of the complete correction system: shown is the amplitude A of the orbit response when exciting a steering magnet with f_{ext}.

CONCLUSION

High bandwidth closed orbit control is essential for acceleration of polarized electrons in a circular accelerator. It is a crucial requirement for the compensation of *integer spin tune resonances* by the harmonic correction scheme. The bandwidth measurements confirm that the closed orbit correction system fulfills the requirements and ensures the correction of all arising resonances even at the maximum acceleration speed.

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