A Beam Diagnostic System for ELSA

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Abstract

A beam diagnostic system, which is based on capacitive beam-position monitors combined with fast electronics, has been developed for the Bonn **EL**ectron **S**tretcher **A**ccelerator ELSA. The position signal of each monitor is digitized at an adjustable sampling rate (max.: 10 MHz) and the most recent 8192 position and intensity values are buffered. This allows a wide range of different beam diagnostic measurements. The main purpose is the closed-orbit correction, which can be carried out on various time scales. To optimize the duty factor of the extracted beam, the system can also be used as a fast relative intensity monitor resolving the intensity distribution of the bunches or of the injected beam. It is designed to support betatron tune and phase measurements with very high accuracy, offering the choice to select any of the beam position monitors. This enables the measuring of many optical parameters. Furthermore any pair of suitable monitors can be used for experimental particle tracking or phase space measurements.

I. INTRODUCTION

The Electron Stretcher Accelerator ELSA, commissioned in 1988, is designed to produce electron beams with a high duty cycle at energies up to 3.5 GeV [1]. The 2.5 GeV synchrotron, in operation since 1967, is now used as an injection-booster. There are three different operation modes for ELSA. In the stretcher mode electrons are injected every 20 msec from the booster. Then the extraction of the electrons is started using a third integer resonance. Above 2 GeV ELSA has to be used in the post accelerator mode. After the injection of several pulses from the booster-synchrotron the electrons are ramped to the required energy (max.: 3.5 GeV). To obtain a satisfactory duty cycle in this mode as well, the extraction time has to be extended. In a third mode ELSA is used as a storage ring for synchrotron-radiation experiments. Due to this multi-purpose usage of ELSA arose the need for a flexible and powerful beam-diagnostic system.

II. THE MONITOR SYSTEM

The ELSA beam position monitor system is based on capacitive pickups[1] with a button-type electrode. A single BPM consists of four electrodes positioned at a 45° angle in a vacuum chamber with a nearly elliptical profile.

A. RF - Electronics

For the signal processing a narrow bandwidth approach was chosen working at a center frequency of 500 MHz with a bandwidth of ± 10 MHz. This is the main frequency component of the beam current in ELSA, since each bucket is filled.

The sensitivity of the pickups was estimated by measuring the amplitude of this frequency component at one pickup button with a spectrum analyser. With 50Ω cable termination this yields an amplitude of 1.1 mV per mA beam current at each button.

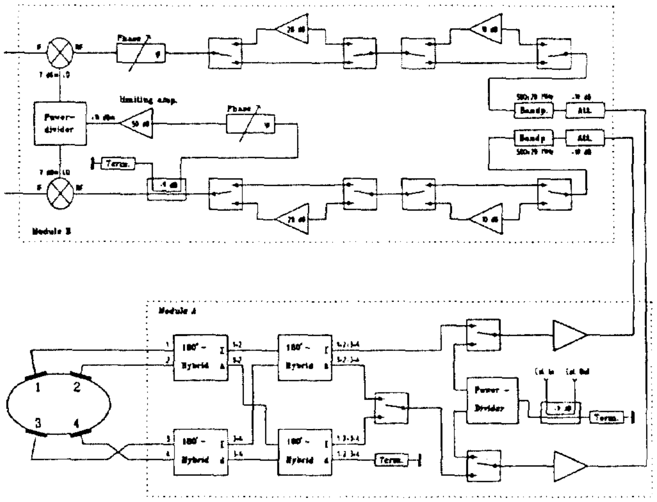

Figure 1
The monitor rf electronics

The signal-processing electronics consists of three different modules. Module A generates 500 MHz horizontal or vertical position signals and an intensity signal. Module B contains amplifiers and the detector circuit for the two 500 MHz signals; the third module carries out the digitization of sum and difference signals. An overview of the whole RF circuit is shown in figure 1. The bottom half of the figure corresponds to the the first rf module. To keep phase errors small the connections between the electrodes and the module have to be short, thus it has to be positioned in the vicinity of the BPMs. The four buttons of the monitor are directly connected to the 180°-hybrids. At the output of the four hybrids we obtain the intensity signal $V_s = V_1 + V_2 + V_3 + V_4$ and the position signals $V_{hor} = V_1 - V_2 + V_3 - V_4$ and $V_{ver} = V_1 + V_2 - V_3 - V_4$.

To reduce the number of channels for the further signal-processing, the horizontal or the vertical signal has to be selected with a GaAs RF-switch, leaving one difference and

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[1] Same type as used at DESY II

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one sum channel. At this point a calibration signal can be switched to both channels with equal phase and amplitude to enable the correction of phase differences or unequal attenuation in the following components. The signal level at the output of module A is increased by an amplifier stage (+13 dB) in each channel.

The two output signals then are carried by two double-shielded coaxial cables to a central station where the other two modules for each monitor are placed. Due to different cable length a special attenuator has to be added for each monitor to obtain an equal overall attenuation for all monitors. At the input of the rectifier-module a bandpass filter with a center frequency of 500 ± 10 MHz is used to remove noise and distortions. A variable amplifier stage, which is realized with two switchable MMIC amplifiers, follows the filter. The detection of the 500 MHz signals is carried out by a homodyne circuit [2] with a dynamic range of 30 dB, which is mainly determined by the limiting amplifier. The two voltage-controlled phase shifters will be used in addition to the calibration signal to correct phase difference in the two channels.

At the output of the mixers we obtain the rectified signal with a bandwidth of 10 MHz and a maximum amplitude of 100 mV. This amplitude range now has to be matched with the input range of the ADC of 0-2 V. A variable gain amplifier, which allows the addition of an voltage offset to the input signal, is used for this purpose.

B. Data Acquisition

The digitization of the signals is carried out by a special sampling module with two 8-bit flash ADCs. The values of the sum and the difference signals are buffered in two static memories of 8 KByte each. The sampling rate can be selected between 78 kHz and 10 MHz. A trigger pulse generated by a microprocessor module (MACS[2]) of the control system starts the data acquisition process for all monitors. It is stopped when the buffer is completely filled.

Control signals for the RF-switches, control voltages for the phase-shifters, for offset and for gain inputs are also generated by this module. Five of this sampling modules can be handled by one module of the control-system.

C. Calibration

The position dependency of the difference signals was measured for each monitor with a movable antenna. A central range of -25..25 mm horizontal and -12..12 mm vertical was covered by the calibration with a step size of 1 mm. For each point a set $(\frac{\Delta_{hor}}{\Sigma}, \frac{\Delta_{ver}}{\Sigma}, x, y)$ was recorded. This data was fitted by a polynomial of 8th degree: $x = P_x(\frac{\Delta_{hor}}{\Sigma}, y)$ and $y = P_y(\frac{\Delta_{ver}}{\Sigma}, x)$. To obtain (x, y) from the position data $(\Delta_{hor}, \Delta_{ver})$ an iteration algorithm is used, usually with less then 10 iterations.

Online calibration of the phase shifters and the data acquisition can be performed by the MACS-modules on request, thus cancelling the effects of temperature or long term drift.

III. SOFTWARE FOR DATA ANALYSIS

A. The ELSA Physics Operating System

For ELSA beam diagnostics and orbit correction in combination with accelerator control, a program named "EPOS" (**E**LSA **P**hysics **O**perating **S**ystem) was implemented based on the existing control system. EPOS combines BPM data aquisition, analysis and automation of measurement and steering tasks in an interactive, workstation-based environment.

The system provides a simple programming language for ELSA control and data analysis. This language gives access to all accelerator and BPM parameters and can manipulate data objects by a variety of different tools, for instance algorithms dealing with closed orbit correction.

EPOS allows the use of expressions, which may include transcendental or special functions, operations on arrays, matrices or optics of the machine, like measured orbits or computed β–values. The digital signal processing module contains different kinds of timedomain–filters, fourier analysis, power spectrum estimation methods and techniques for peak detection, trend removal and data smoothing. Additionally instruments for curve fitting, interpolation and histogramming are available. The graphical user interface of EPOS is based on `X-WINDOWS` and `GKS` and can generate plots and printouts for all supported data types.

B. Closed Orbit Correction

The closed orbit correction is performed via steering dipoles. Their settings are calculated by the program COCPIT (**C**losed **O**rbit **C**orrection **P**rogram for **I**nteractive **T**asks), which is integrated into EPOS.

First the quadrupole field gradients are evaluated from the machine tune, since the tune can be measured with high accuracy. Then the optical functions are determined. A matrix $\mathcal{M}$ is evaluated which gives the expected beam positions at the BPMs for a given set of steerer stettings. With this a least-square correction can be performed by inversion of $\mathcal{M}$, but harmonic correction is implemented as well. Due to the resonant structure of the betatron motion, high frequency components (with respect to the tune) of the closed orbit are expected to be strongly suppressed for a random distribution of field errors. On the other hand when correcting with LSQ method, high frequency components of the closed orbit produce extreme steerer settings. COCPIT allows to select a frequency range and perform correction only for frequency components inside this range (harmonic correction). The Fourier transformation and necessary filtering can be put together to one matrix $\mathcal{M}'$, given by

$$m'_{ij} = \frac{\sqrt{2}}{\sqrt{\beta_i \beta_j}} \sum_{k \in range} \frac{Q^2}{Q^2 - k^2} \sin(\frac{\pi}{4} + k \Delta\phi_{ij}),$$

with i and j denoting the positions of BPM and steerer respectively. Thus the calculations can be performed in

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[2] Microprocessor Aided Control System, developed at Bonn.

complete analogy to the LSQ method and in the same time. Single monitors can be weighted with errors or completely left out of the calculations, when they are supposed to be erroneous. Also single steerers can be switched off or set to a current limit for the calculations to avoid overloading.

IV. MEASUREMENTS

A. Closed Orbit

To test the accuracy of the monitors the dispersion versus the detuning of the accelerating rf was measured. For different frequencies the beam's position was taken at all monitors. A straight line was fitted to each monitor's data and this line's maximum deviation from the data points was taken as an upper limit of the monitor errors. This yields an accuracy better than 0.2 mm.

Closed-orbit corrections were carried out with both correction schemes. The LSQ correction seems better to cope with the huge deviations of the uncorrected orbit while the harmonic correction produces the best results when used as the second correction. With both algorithms a final rms-value of 0.15 mm and maximal values of ±0.25 mm can be obtained.

B. Betatron Tune

The transverse tune of the machine is measured by analyzing the beam position data taken from a coherent betatron oscillation. The oscillation can be observed after the injection or can be induced by a kicker magnet. A Fourier transformation is applied on the position data, the fractional tune value is derived from the measured betatron sideband frequency, related to the ELSA revolution frequency of ≈1.8 MHz. The loss of coherence limits the useful beam observation time of the BPM system to $\approx 200\mu$sec, which yields a tune resolution in the range of $\frac{\Delta Q}{Q} \approx 10^{-3}$. For slow resonant extraction (as required by the stretcher principle) near a third integer resonance, however, this accuracy of $\frac{\Delta Q}{Q}$ is not sufficient. To increase accuracy, a special correction method was implemented in the EPOS spectral analysis software. By using an interpolation recipe for the main bins of a detected spectral peak, it is possible to get a $\frac{\Delta Q}{Q} \approx 10^{-4} - 10^{-5}$. By combining this method with the computation of the weighted mean for selected peak bins, the tune measurement has been made possible with a reliable resolution of $\frac{\Delta Q}{Q} \leq 10^{-4}$. Thus, a fine-adjustment of the controlled tune-shift (by fast quadrupoles) during the extraction period can be performed very easily.

All tune measurements are automatically performed by the EPOS system, which is also used to apply more diagnostic methods to the obtained position spectra.

C. Phase Space

First measurements of the phase space for different tunes were carried out by recording the coherent betatron oscillation in the horizontal plane at two neighbouring BPM stations. To keep calculations simple two BPMs were chosen where $\beta_i = \beta_j$ and $\phi_i - \phi_j \approx 90°$. For these measurements the four signals of the two monitors were recorded by digital oscilloscopes with a sampling rate of up to 100 MHz. The position value of one bunch ensemble is extracted with a software filter for each revolution out of the recorded signals. Plotting the position values at the second BPM versus the position values at the first BPM shows the phase space in relative coordinates at the position of the first BPM.

Figure 2 shows the evolution of the phase space plot for a horizontal betatron tune close to $4\frac{2}{3}$ and extraction sextupoles in ELSA driving a third-integer resonance. After 30 turns (left figure) the shape of the characteristic phase space triangle appears. After 400 turns the loss of coherence pretends a damping of oscillations.

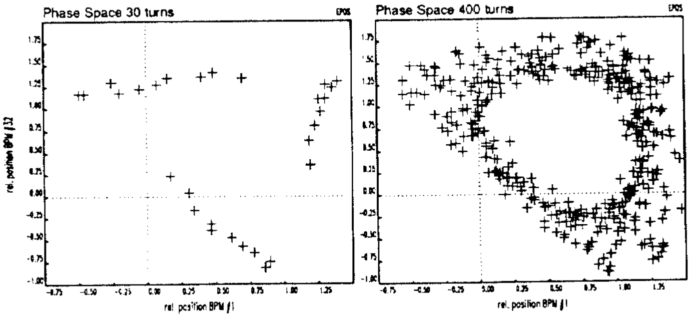

Figure 2
Phase space plot

The formula:

$$\cos 2\pi Q = \frac{1}{2} \frac{x_n - x_{n+1} + x_{n+2} - x_{n+3}}{x_{n+1} - x_{n+2}}$$

can be used to measure the fractional part of the horizontal betatron tune Q on a short time scale of four turns (2.192 μs). This method was used to analyse the dynamical evolution of the horizontal tune for some hundred turns after the injection. Due to energy oscillations a modulation in the kHz-range on the fractional part of the betatron tune can be observed. When the RF in ELSA is switched off a constant rise in the horizontal tune can be seen, that is caused by the energy loss according to synchrotron light emission.

V. REFERENCES

[1] K.H. Althoff et al., "ELSA - One Year of Experience with the Bonn Electron Stretcher Accelerator," in *Particle Accelerators, Vol. 27*, pp. 101–106, 1990.

[2] R. Bossart, J. Papis, and V. Rossi, "Synchronous RF-Receivers for Beam Position and Intensity Measurement at the CERN SPS Collider," in *IEEE Trans. Nucl. Sci. NS-32*, p. 1899.