Nuclear Inst. and Methods in Physics Research, A 890 (2018) 18–27

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Comparison of beam position calculation methods for application in digital acquisition systems

A. Reiter *, R. Singh

Beam Instrumentation Department, GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany

A R T I C L E I N F O

MSC:
00-01
99-00

Keywords:
Hadron accelerator
Beam position monitor
Data analysis
Uncertainty
Robustness
Least-squares method

A B S T R A C T

Different approaches to the data analysis of beam position monitors in hadron accelerators are compared adopting the perspective of an analog-to-digital converter in a sampling acquisition system. Special emphasis is given to position uncertainty and robustness against bias and interference that may be encountered in an accelerator environment.

In a time-domain analysis of data in the presence of statistical noise, the position calculation based on the difference-over-sum method with algorithms like signal integral or power can be interpreted as a least-squares analysis of a corresponding fit function. This link to the least-squares method is exploited in the evaluation of analysis properties and in the calculation of position uncertainty. In an analytical model and experimental evaluations the positions derived from a straight line fit or equivalently the standard deviation are found to be the most robust and to offer the least variance. The measured position uncertainty is consistent with the model prediction in our experiment, and the results of tune measurements improve significantly.

1. Introduction

Beam position monitors are non-interceptive detectors that are crucial to the operation of linear accelerators, synchrotron accelerators or storage rings. Exploitation of their signals gives access to a wealth of information beyond the individual transverse bunch position, including the more complex lattice optics measurements of fractional tune, chromaticity, dispersion, beta functions, and phase advances. Further dedicated measurements of intra-bunch oscillations, of transverse impedances, and of high-intensity effects are routinely performed using these systems. Nowadays signals are acquired in powerful sampling systems which offer the freedom to analyze online the incoming data stream with methods of digital signal processing in field programmable gate arrays. The system performance depends on the quality of position calculation.

The genesis and focus of this study has been the reliable operation of FAIR synchrotrons [1] under several operational scenarios such as stacking, multi-turn injection, bunch merging and splitting, longitudinal bunch shrinkage during the acceleration ramp, while being least affected at the same time by imperfections like an offset (bias) in amplifier or analog-to-digital converter, or low-frequency "interference" in the acquired signal. For these hadron accelerators several samples are available even for the shortest bunches, and therefore the position analysis can be carried out in time domain.

Two topics were of special interest: position uncertainty, which receives little attention in available literature, and reliability in day-to-day operation. The primary objective was the selection of the "best" analysis judged by robustness, uncertainty and ease of implementation. One of the difficulties for such a comparative study stems from contrasting requirements, e.g. for "fast" turn-by-turn positions sometimes referred to as "beam trajectory" and a "slow" averaged position over several turns also referred to as "beam orbit". In this report, we propose a single optimal approach for dealing with both the cases.

In the framework of a statistical analysis we have studied some of the most common algorithms applied in the difference-over-sum method. A new approach of position calculation on the foundation of a least-squares analysis is presented. It offers a different view onto the expected properties of results. The predictions of the analytical model have been backed by measurements with the position monitor system of the SIS-18 synchrotron at the GSI facility. The robustness was studied by introduction of offsets or an external frequency to experimental data prior to position and fractional tune analysis.

Section 2 introduces the beam position monitor system, the fundamental difference-over-sum method and our requirements for a robust position analysis. Position algorithms are briefly discussed in Section 3. Their relations to the least-squares method are established in Section 4 which are exploited to investigate properties of results in some more

* Corresponding author.
E-mail address: a.reiter@gsi.de (A. Reiter).

https://doi.org/10.1016/j.nima.2018.02.046
Received 24 November 2017; Received in revised form 7 February 2018; Accepted 9 February 2018
Available online 14 February 2018

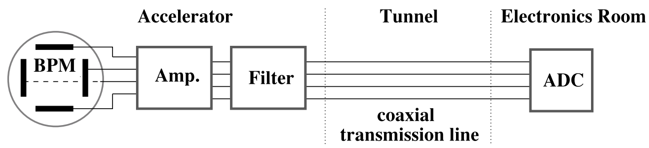

Fig. 1. Schematic of BPM data acquisition system consisting of BPM with horizontal and vertical electrode pairs, four channel amplifier and ADC sampling system.

depth. In Section 5 we present experimental data on uncertainty, a study of position robustness against added interferences, and a comparison of tune spectra. The latter proves that the analysis of derived quantities can benefit significantly from an appropriate choice of position calculation method. The conclusions drawn from our work are summarized in the last section.

2. System layout and data analysis

2.1. Detector and hardware

We consider a linear horizontal beam position monitor (BPM) with constant position sensitivity s_X, a coefficient that relates the detector output to a change in beam position. Fig. 1 illustrates a minimal hardware setup consisting of symmetric electrode pair, amplifier, filter, coaxial transmission line, and bipolar analog-to-digital converter (ADC) system. BPM capacitance C and amplifier input resistance R form an CR differentiator or high pass filter. Its transfer impedance Z is discussed in [2] and tends to unity for our case of high-impedance in our frequency range of interest. Hence, the recorded signals are proportional to the beam current j_{beam}.

For a fixed beam position, we assume a strict proportionality between left and right electrode signal, since the displacement currents $j_{L/R}$ induced by the pulsed beam are defined by the time derivative of the electric field over the electrode surfaces:

$$j_L(t) \propto j_R(t) \propto j_{beam}(t) \tag{1}$$

Both electrode currents are supposed to be connected to a matched amplifier pair, i.e. amplifiers of identical gains followed by a matched filter which represents a versatile element that could be a band-pass filter, a frequency down converter or any linear analog signal processor. In the hardware setup of the SIS-18 hadron synchrotron at GSI, it is simply an all pass filter. Following that is an ideal ADC of fixed, bipolar input range and maximum input span V_{FS}. The filter output signals are called $S_L(t)$ and $S_R(t)$, respectively, and preserve the proportionality $S_L(t) \propto S_R(t)$. After digitization, they are functions of the sample number i or sample time $t_i = i \cdot t_{Sa}$ where t_{Sa} is the sampling interval.

Fig. 2 presents a digitized signal recorded after acceleration in the synchrotron SIS-18 where a smooth pulse shape is observed. N_S indicates the number of signal samples, i.e. samples with an amplitude above the baseline level. Between two bunches there are N_B baseline samples, and a subset of size N_O may be used for baseline restoration. The baseline droop caused by the AC coupling in the electronics and its effect on position measurement is discussed in the next section.

The noise voltage σ_V, that is the uncertainty of a single ADC datum, is defined by the standard deviation of a baseline (or offset) measurement, performed when no external stimulus acts on the BPM electrodes, or is given by the effective number of ADC bits whichever is larger [3]. Hence, this definition of the uncertainty σ_V includes all noise contributions along the signal chain. We assume a constant value for σ_V independent of the measured signal level. However, we should note that the noise characteristics of a realistic amplifier and ADC cannot be fully specified by a single number since the frequency spectra are not "white", and therefore σ_V is not the same for all position analysis methods [4].

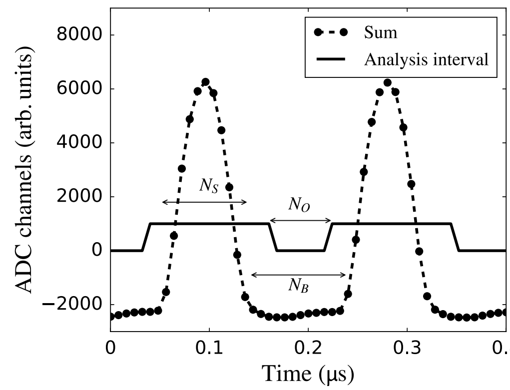

Fig. 2. Sum signal of bunches at the extraction flat-top for BPM V1. The generated analysis intervals around the bunch for position calculation are shown.

2.2. AC coupling, offset and baseline restoration

BPM electrodes and amplifier form an AC coupled system with high-pass characteristic with lower cutoff frequency $f_{cut} = (2\pi RC)^{-1}$ [2]. At hadron accelerators the case of high impedance is very common to boost signal levels. For our 1 MΩ high impedance system $f_{cut} \approx 1.5$ kHz, if a capacitance $C = 100$ pF is assumed. The baseline returns to zero with a characteristic time constant $\tau = RC = 0.1$ ms, a long time compared to a typical revolution period t_p in the microsecond region and below. For repetitive bunches AC coupling leads to baseline drifts or offsets if $t_p \ll \tau$ as in the present case. Detailed discussions on this subject can be found in [5,6].

For a single short bunch in a beam transfer line, this effect can be neglected. If several bunches are transferred, the baseline offset can become relevant depending on number and separation of bunches. A stable, circulating beam in a synchrotron will result in a balanced system with constant baseline offset as shown in Fig. 2. There, it can be calculated directly from a subset of N_O samples between two bunches. For turn-by-turn data the offset O can also be calculated from the boundary condition of zero mean current (due to AC coupling). We assume a constant value between two successive pulses of length $t_s = N_S \cdot t_{Sa}$ separated by the repetition period $t_p = (N_S + N_B) \cdot t_{Sa}$:

$$\begin{aligned} 0 &= \int_{t_0=0}^{t_p} (S(t) - O)\, dt = \int_{t_0=0}^{t_s} S(t)\, dt - \int_{t_0=0}^{t_p} O\, dt \\ &= I - O \cdot t_p \quad \Rightarrow O = \frac{I}{t_p} \end{aligned} \tag{2}$$

Since the offset is proportional to the mean signal it stores information on the average position on a slow timescale defined by τ. But, for fast beam movements the present offset value is an arbitrary number. The same is true for stacked operation where baseline offset due to the stored beam and new position of the last injection are entirely decoupled.

Another problem is presented in Fig. 3. This irregular pulse was recorded at injection into the synchrotron and shows no distinguishable baseline. Other complex shapes may be generated during bunch merging or splitting at a later stage of the synchrotron cycle. For such signals the existing beam-based implementation of bunch detection at the SIS-18 synchrotron [7] fails to generate stable analysis windows. Irregular structures makes any restoration prone to systematic effects and limit the achievable position accuracy since the offset is calculated from a limited number of samples. In the last stage of the hardware, signal offsets may be introduced when the ADC offset is drifting or incorrectly adjusted. Therefore, we search for a position analysis that does not need to differentiate between signal, baseline or offset samples and that is independent of offsets in order to avoid baseline restoration altogether.