DIGITAL BASE-BAND TUNE DETERMINATION

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Abstract

To avoid beam losses of intense beams stored at the GSI heavy ion synchrotron SIS18 a precise tune measurement during a whole acceleration cycle is required. This contribution presents a sensitive method of tune determination using data of Beam Position Monitor (BPM) measured in bunch-by-bunch manner. The signals induced in the BPM electrodes were digitized by 125 MS/s and integrated for each individual bunch. The tune was determined by Fourier transformation of the position data for typically 512 subsequent turns. Coherent betatron oscillations were excited with bandwidth-limited white noise. The presented method allows for tune measurements with satisfactory signal-to-noise ratio already at relatively low beam excitation i.e. without significant increase of transverse beam emittance. In parallel the evolution of transverse beam emittance was monitored by means of an Ionization Profile Monitor. The system for online tune measurement is an integral part of the new digital BPM System, presently under commissioning.

INTRODUCTION

Unlike other beam parameters, e.g. beam current, position, transversal beam profile etc., the tune is a crucial beam parameter that can not be obtained in a single individual measurement. A most fundamental technique is based on the excitation of coherent transversal beam motions with a known perturbation source and post-processing of the beam response using beam position monitors (BPM).

The GSI heavy ion synchrotron SIS18 has some particular machine parameters, which make tune diagnostics challenging. Namely the comparatively long bunches, the injection at non-relativistic velocity β = 15.5% and the fast ramping of the acceleration frequency from 0.8 to 5 MHz within 400 ms. Since tune measurement during a whole acceleration cycle is required, other methods of tune determination using e.g. passive monitoring of the residual beam oscillation (like observation of Schottky noise) or active techniques based on phase-locked-loop systems are either to slow or require a lot of manpower during implementation. For an overview see e.g. [1] and references therein.

On the other hand, a new data acquisition system for BPMs at SIS18 presently under commissioning [2] opens new possibilities for tune determination. Since the beam position is measured in bunch-by-bunch manner it was evident to investigate if the tune can be determined by appropriate post-processing of anyhow existing beam position data. The results of these investigations are presented and discussed in the following sections.

For a stable beam consisting of a large but finite number of particles a movement of the centre-of-mass is the incoherent sum of individual particle oscillations effected by random phases and frequency spread. This so called *Landau damping* [3] makes the betatron motions of individual particles inaccessible. Usually the residual coherent particle motions are too weak to be detected and the beam needs to be slightly excited. There are three methods of the beam excitation available at SIS18:

- One-turn kick-type excitation using a pulsed magnet that applies its full power within a single revolution period. However, the transversal motions decay within some hundreds of turns due to Landau damping which excludes the possibility of tune observation over the whole acceleration cycle.
- Frequency sweep excitation: generated using a sinusoidal-type signal with time-varying frequency. However, for fast ramping accelerators like SIS18 the increase of the SIS rf frequency is faster compared to the sweeps performed by the exciter which does not allow for tune diagnostics on the acceleration ramp.
- Noise excitation which considers an excitation with a broadband noise covering the expected frequency range.

For the investigation presented in this contribution the last method was used.

METHODS AND RESULTS

Fig.1 shows schematically the detection setup. The beam was excited using a noise applied to the exciter plates installed at SIS18. The noise signal with adjustable bandwidth around the side bands of the carrier frequency

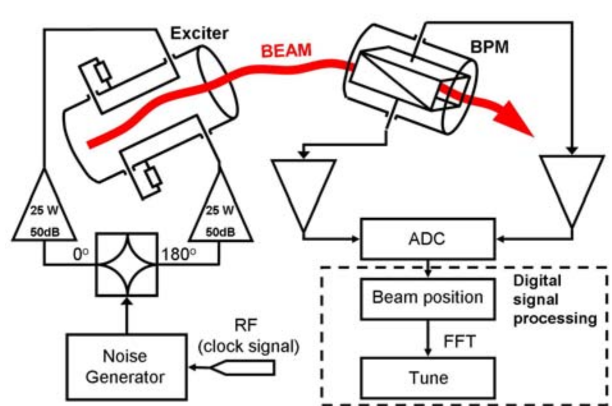

Figure 1: Detection setup (see description in text).

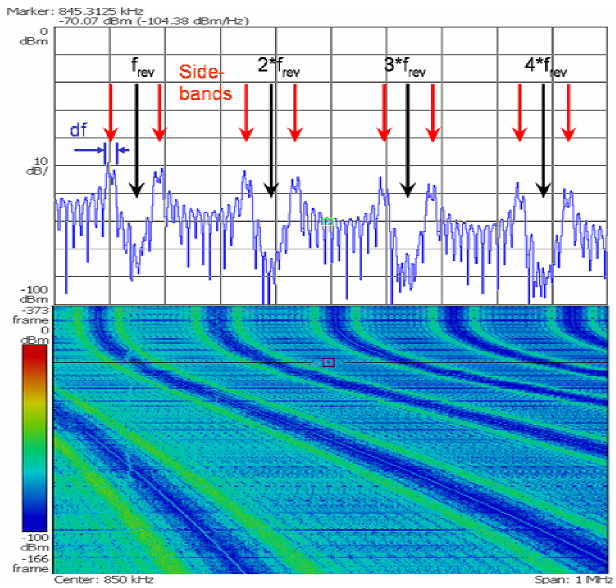

Figure 2: Frequency spectrum of the pseudo random noise generator. The first four harmonic frequencies are seen (top). The noise bandwidth df corresponds to Δq=0.05. The carrier frequency is locked to the SIS18 acceleration frequency (bottom).

was produced by means of Digital Pseudo Random Noise generator [4]. The frequency spectrum of the noise signal is shown in Fig.2. The carrier frequency follows the acceleration rf by using a frequency tracker. The noise bandwidth df is chosen to be broad enough to cover the maximum expected tune deviation from the set value which, in the particular case of SIS18, usually does not exceed Δq=0.05. The signal of the noise generator was split using a 180^O hybrid, amplified up to a maximal power of 2*25 W and fed to a 750 mm long stripline exciter having horizontal/vertical apertures of 200x70 mm^2, respectively. Note that Fig.1 shows only one half of the system, e.g. for the vertical tune measurement; analogical system components are used independently for the measurement of the horizontal tune.

The beam response was observed using one of the 12 regular BPMs. The broadband analog signals from all four plates of a diagonal-cut type pick-up [5] were fed to an amplifier with high input impedance and digitized by a 14 bit ADC with a sampling rate of 125 MSa/s. For typical SIS18 beam parameters this corresponds to about 140 Sa/bunch at injection and about 20 Sa/bunch at extraction, respectively. In a digital signal processing, after restitution of base line shift [6], the signals are integrated bunch-by-bunch within the integration windows. The integration windows are generated from the input signal itself as described i.e. in [7]. The output of this beam position algorithm was one value for the vertical and one for horizontal beam position, calculated for each individual bunch using the delta-over-sum method [8].

The fractional tune is calculated by Fast Fourier Transformation (FFT) of position values for the given bunch typically over 512 turns. In FFT computation subsequent bunch positions are treated as equidistant. This implies that the obtained frequency spectrum is per definition normalized to the revolution frequency f_{rev} of the ions within the synchrotron i.e. is automatically transformed into a base-band. The resulting fractional tune spectrum is expressed in units of f_{rev} and ranges from $0 < q < 0.5$ (see Fig. 3). Typically more than one bunch is circulating in SIS18 (usually 4 bunches). In this case the number of calculated FFTs is equal to the number of circulating bunches. A final spectrum (as the one shown in Fig. 3) represents an average of all FFT results.

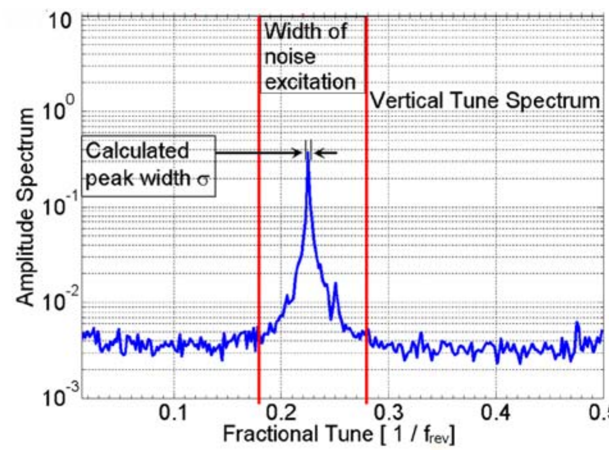

Figure 3: Typical vertical tune spectrum for a beam of 6.5 x 10^9 Ar^{18+} ions obtained in FFT over 512 turns. The red lines depict the bandwidth of the excitation signal.

Fig. 4 presents results obtained for a complete acceleration cycle. A beam of 6.5 x 10^9 Ar^{18+} ions was accelerated from 11.4 MeV/u to 300 MeV/u within 400 ms, which corresponds to 220.000 turns. The upper part of Fig. 4 shows the vertical beam position over the whole acceleration cycle. To increase the resolution of position read-out an average over 1000 turns is calculated.

For each block of 512 subsequent turns the FFT is calculated resulting in the tune distribution over the acceleration cycle shown in Fig. 4 (bottom). For each point of this curve the mean position of the peak in FFT spectrum was determined. For the beam parameters mentioned above one obtains about 400 points per second. A measured tune diverges from the preset one. While the value for the vertical tune was preset to 3.23 the measured mean fractional tune is 0.221 and varies over the acceleration cycle within ±0.005.

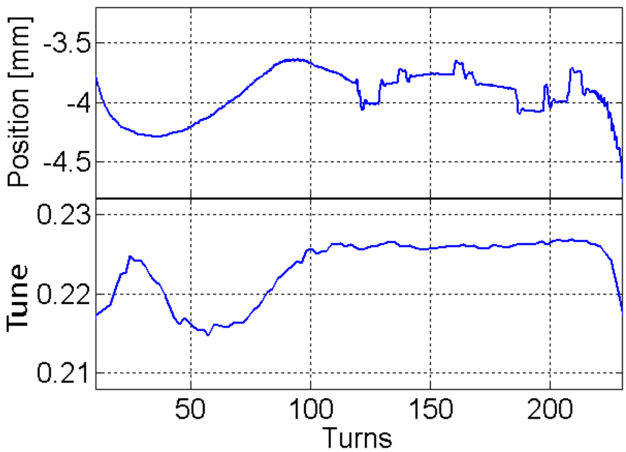

Figure 4: Vertical beam position (top) and vertical fractional tune (bottom), see text for beam parameters. Excitation at q_{ex} = 0.23 ± 0.05 with amplitude of P_{ex} = 3.5 W.

Determination of optimal excitation strength

The above mentioned Landau damping is actually the main mechanism leading to transversal emittance blow-up: While the observed centre-of-mass motion decays, the sum of the individual particle energies is preserved. In hadron accelerators such as SIS18, that are practically unaffected by synchrotron radiation losses, there is no mechanism that could lead to damping of the incoherent oscillations of the individual particles. Therefore it's necessary to avoid excessive excitation of the beam as it leads directly to emittance blow-up and, in consequence, to particle losses. On the other hand there is a certain excitation strength needed for proper tune measurements. In order to determine the ideal range of excitation power a series of measurements was performed with different excitation strength, whereas all other beam parameters remained unchanged. The exciter power was increased from zero to the maximum possible excitation power of 50 W (this value corresponds to a power spectral density (PSD) of 0.72 mW/Hz).

The signal-to-noise ratio presented in Fig. 5 (top) was calculated by comparison of the integral underneath the tune peak in the Fourier amplitude spectrum (Fig.2) to the same width of the noise flour i.e. a part of the spectrum of equal width but outside the resonance. Each data point in Fig. 5 (top) is an average of 26 acceleration cycles. The fluctuations are represented in the error bars.

Simultaneously to the tune measurements the beam intensity and the beam profiles were recorded. The influence of beam excitation on the transversal emittance was observed by measurements of the horizontal and vertical beam profiles using an Ionization Profile Monitor (IPM) [9]. The dependency of the beam width on the beam excitation strength is shown in Fig.5 (bottom). Each data point is an average of 60 acceleration cycles, whereas the error bars indicate a maximum deviation of the single measurement from the mean value. Starting from a beam excitation of about 8 W a measurable beam broadening is observed. In addition data from the DC Current Transformer (DCCT) were analyzed in order to detect the beam losses, see Fig. 5 (middle). For the DCCT data an average of 100 measurements is taken.

A 'working area' can be defined as follows: For an exciter power of about 2 W (PSD = 0.029 mW/Hz) the S/N ratio reaches a factor of three which is sufficient for stable tune determination. On the other hand no significant beam loss exceeding 2 % was observed for excitation levels below 8.5 W (PSD = 0.12 mW/Hz). Hence, the working area can be defined to the range 2-8.5 W. Of course these values are only valid for the SIS18 beam parameters listed above since they depend on charge state, ion mass and energy ranges. However, similar measurements can be done for other ion species and energy ranges almost online.

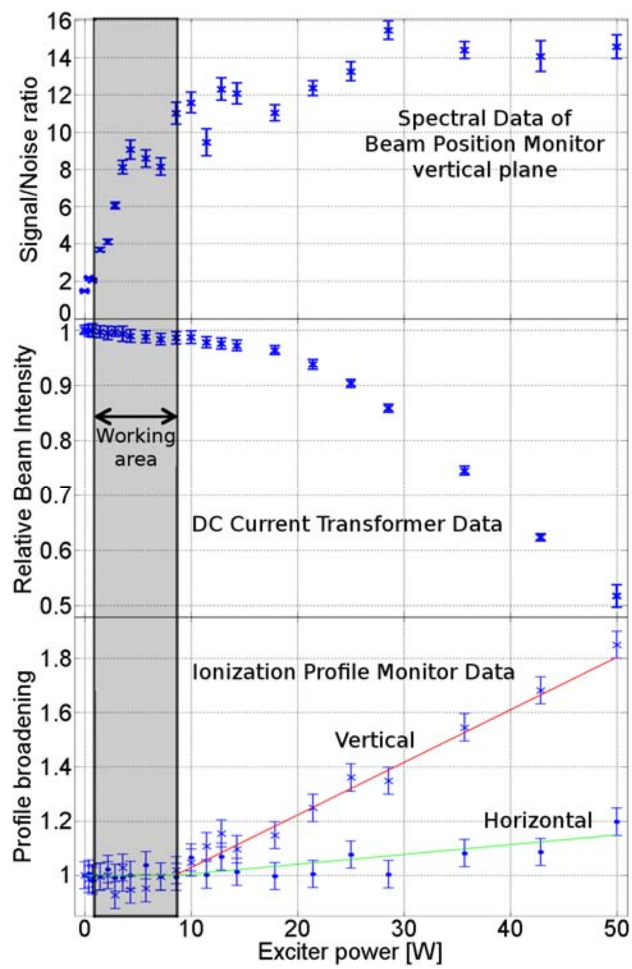

Figure 5: Influence of beam excitation using band limited noise on the signal–to-noise ratio of the tune signal (top), beam loss (middle) and beam profile (bottom). For measurement parameters see text.

Another interesting issue can be pointed out, when analyzing the bottom part of Fig. 5: Though, the beam was excited in vertical direction only, there is a measurable response in the horizontal plane. This coupling is commonly referred to a betatron coupling and is an evidence of the skew quadrupole components caused by e.g. tilts of lattice quadrupole magnets or offsets in lattice sextupole magnets.

SUMMARY AND OUTLOOK

The base-band digitization of BPM signals together with band-limited white noise excitation of the beam allows precise tune determination on the synchrotron ramp. The measurements yield reproducible results on a low excitation level using a PSD of below 0.1 mW/Hz, thus defining the right working range for tune measurements and preventing detrimental emittance blow-up. Displaying the measured machine tune with a resolution of $\Delta q < 2*10\text{-}3$ next to a precise beam position with a resolution below 30 µm gives a powerful tool for machine operation and is a good alternative for the analog based high sensitive base-band tune detection system [10].

The advantage of the digital system is fourfold:

- Integration of each individual bunch over many samples does not only increase the effective ADC granularity but also reduces contributions of stochastically distributed perturbations like thermal or digitization noise.
- An integration of bunch signal is performed within the windows generated on the signal itself. The window width is optimally adjusted to the width of the bunch, which acts as a filter with optimal and variable bandwidth. This is extremely advantageous especially for accelerators like SIS18 with long bunches and acceleration frequency changes exceeding a factor of 5.
- Since the tune is calculated as FFT of the position data that are treated as equidistant, the tune is automatically normalized to the base-band without any additional external parameter.
- In the particular case of SIS18, where four bunches are present in the cycle, the purely digital signal treatment allows for easy selection of one single bunch. This allows removing tune signal smearing due to the eventual difference in the phase of betatron motions between the accumulated bunches. It corresponds to the gating as used in analog tune measurement systems [11].

The tune measurement presented here requires a very cautious procedure of bunch recognition: Losing even one single bunch introduces a phase offset that diminishes the measurement resolution.

The presented system is a promising prototype for tune measurements at FAIR and is actually being implemented at SIS18.

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