REAL -TIME BETATRON TUNE MEASUREMENT IN THE ACCELERATION RAMP AT COSY – JÜLICH

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Abstract

A new real-time method for betatron tune measurements at COSY was developed and tested from the early 1997. A bandlimited broadband noise source was used for beam excitation, the transversal beam position oscillation was bunch-synchronous sampled and digitized with a high resolution ADC. The Fourier transform of the acquired data represents immediately the betatron tune. After the first promising experiments an automatic tunemeter was constructed. The tunemeter is used as routine diagnostic tool since end of 1998.

1 INTRODUCTION

The cooler synchrotron and storage ring COSY, with a circumference of 184 m and single bunch, delivers medium energy protons. The corresponding revolution frequencies in the acceleration ramp are between 0.45 MHz (flat bottom) and 1.6 MHz (flat top). For beam diagnostic measurements magnetic impulse kicker [1] and broadband stripline exciter [2] can be used. The mode of excitation and the strength can be automatically set. A basic task for beam diagnostic is the measurement of the tune in the acceleration ramp.

The betatron tune (Q) is the quotient of the frequency of the betatron oscillation and the particle revolution frequency. The betatron frequency ($f_\beta = Q * f_0$) is usually higher than the revolution frequency, but only the fractional part (*q*) of the betatron tune can be measured:

$$f_\beta^n = n * f_0 \pm Q * f_0 = (n' \pm q) * f_0 .$$

For tune measurements the betatron oscillation of the particles is resonantly enhanced by RF-excitation via the stripline unit. Beam position monitors (BPM) [3] with low noise broadband amplifiers deliver signals proportional to the beam response on the excitation. The sampled and digitized difference signal is processed for monitoring the betatron tune. A bunch-synchronous pulse train, necessary for the sampling, is derived from the sumsignal of the same BPM.

2 SYNCHRONOUS SAMPLING AND FFT

Performing the discrete Fourier transformation of N subsequently acquired samples follows:

$$S\left(\frac{m}{NT}\right) = \sum_{n=0}^{N-1} s(nT) * e^{-j(2\pi nm)/N}$$

with T time interval of the samples,

$s(nT)$ the n-th sample of an array of N samples

$S\left(\frac{m}{NT}\right)$ the m-th Fourier component at $f_m = \frac{m}{NT}$

The frequency of a Fourier component relates to the sampling frequency ($f_S = 1/T$). Due to the bunch-synchronous sampling the frequencies in the FFT array are normalized to the revolution frequency.

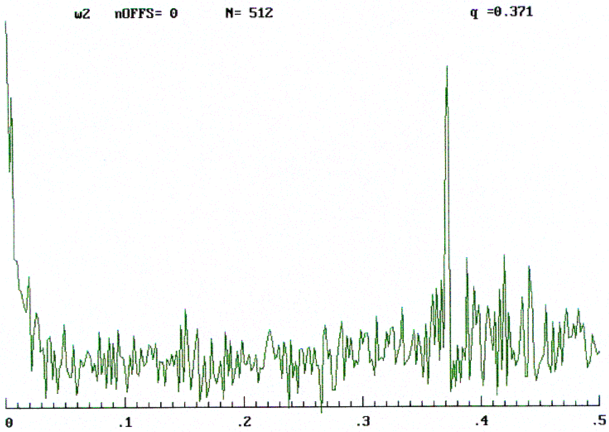

Figure 1: Betatron line in the normalized frequency domain

A sideband caused by the betatron oscillation appears as a peak in the normalized frequency domain. Fig. 1. shows a sideband line in the spectrum [4]. Because of using the revolution frequency as sampling frequency, it follows:

$$q * f_0 = f_q \Leftrightarrow f_{m'} = \frac{m'}{N} * f_0 \qquad \text{therefore}$$

$$q = \frac{m'}{N} \qquad 0 < q \text{ or } (q-1) < 0.5$$

In the normalized frequency domain the tune value is directly shown. The frequency f_m of the m-th datapoint ($m = 1,.., N / 2$) is $f_m = m / NT$ with $1 / T = f_S = f_0$. If f_m' is the frequency of the sideband it follows $f_m' = m' / N * f_0$ and due to $f_m' = q * f_0$ then: $q = m' / N$. Using $f_S = 1$ the normalized frequency corresponds immediately to the fractional tune.

3 TUNEMETER CONFIGURATION

Via the stripline unit coherent betatron oscillations in horizontal and vertical direction can be raised by means of broadband transversal excitation [5]. The cumulating effect of the subsequent excitations on the circulating beam results in a coherent oscillation at resonance frequencies only, other components of the excitation are neutralized and therefore have virtually no effect on the beam.

A white noise source generates the exciting signal. Bandpass filter with fixed cutoff frequencies (BW= 100 kHz – 2 MHz) limits the excitation bandwidth. The frequency range of the noise covers always at least one betatron sideband at the fundamental harmonics in the whole ramp without frequency feedback. The excitation can be enabled/disabled by means of a fast GaAs switch controlled by either remote commands or a timer unit. The programmable excitation level changes in real-time.

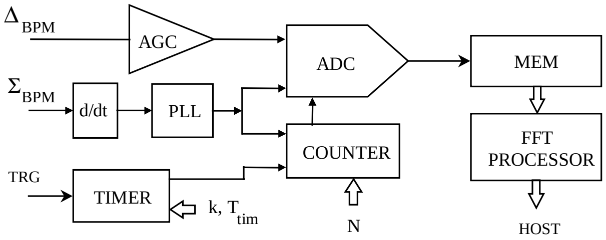

Figure 2: Block diagram of the FFT tunemeter.

A beam position monitor picks up the beam response on the excitation. Low noise gain controlled amplifiers control the level of the sum and difference signals. The bunch-synchronous pulse, necessary for the sampling, is derived from the sum signal of the same BPM. Phase locked loop with narrowband loop filter generates clock pulse with low tracking jitter in the whole range between injection and flat top. With proper signal processing the clock generator tracks also the synchrotron oscillation. For investigation of the synchrotron oscillation a signal proportional to the synchrotron oscillation can be also derived from the tracking circuitry of the clock generator. A high resolution ADC digitizes the difference signal.. The timers of the measurement trigger and of the excitation gate are synchronized. Fig.2 shows the block diagram of the FFT tunemeter.

4 SIGNAL AND DATA PROCESSING

The betatron oscillation appears as an amplitude modulation on the beam position signal evoking double sidebands around each harmonics of the revolution frequency and also around DC in the spectrum of the position signal of the bunched beam. The peak value of the BPM difference signal, proportional to the beam position, will be sampled by means of a fast sample and hold circuitry and digitized with a high resolution ADC. The positive edges of the bunch-synchronous clock start the sampling at the bunch peaks i.e. at the highest betatron amplitude. The gain controlled amplifiers grant an optimal utilisation of the 14 bit ADC. The peak value of subsequent bunches carrying the betatron oscillation will be recorded. The Fourier transform of this array invokes the fractional betatron tune.

This method combines the functions of a synchronous demodulator and a frequency normalizer. Due to the bunch-synchronous sampling the frequency components of the synchrotron oscillation are suppressed. The sampled data therefore contain mainly the betatron sidebands transposed into the range between DC and f_0 /2. The lowest normalized frequency is zero (DC component), the usable highest is f_0/2, the corresponding range of q or (1-q) is between 0 and 0.5. Subsequently acquired spectra with the same time intervals are displayed as a waterfall diagram showing the tune as a function of the time (Fig.3.) On the left edge of the screen the values of the detected tune peaks are also numerically displayed.

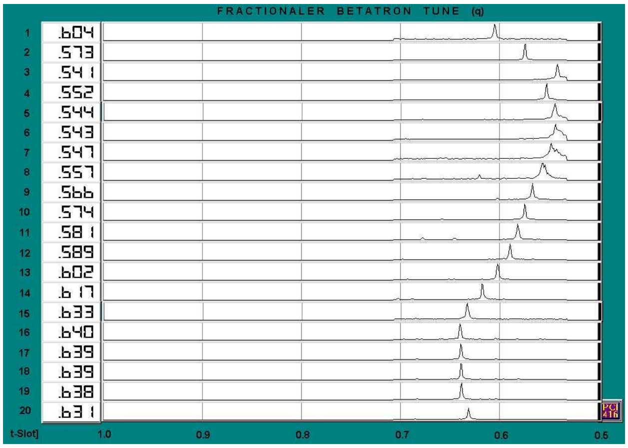

Figure 3: Display of a tune measurement in the ramp consisting of averaged FFT spectra

The beam rigidity is low in the lower energy range, therefore very weak excitation is adequate for a distinct betatron response. In the ramp the excitation strength has to be increased. The time function of the excitation level is programmable. It is held as low as possible for an optimum of signal to noise ratio and as small as possible particle loss. For this reason the excitation is switched on only for the duration of the data acquisition by means of a fast GaAs switch. The data are taken in blocks of N datawords each and are stored sequentially in memory. For start the COSY timing system triggers an internal timing logic, which in turn generates k timing pulses with constant time interval for k tune values. The number k of timing pulses and their interval must be properly chosen, in order to obtain the tune measurement time overlapping the total acceleration ramp time as desired. In a data acquisition cycle k∗N samples corresponding k tune value are sequentially acquired.

The acquired datablocks are transformed by FFT resulting in frequency spectra with N / 2 datapoints. As the duration of the acquisition depends on N, its value must be properly chosen, because it determines the frequency resolution of the FFT-spectra (equal to 1 / NT with $1 / T = f_s$, here $1 / T = f_0$). Although the duration changes in the acceleration ramp, the resolution of the tune (1 / N) is constant. As shown above, the bigger the quantity of the samples in the array used for evaluation the higher the frequency resolution and consequently the accuracy of the tune measurement.

The average acquisition time ($N * T_0$) for a tune resolution of $5 * 10^{-3}$ is less then 2 ms. The transformation of a record needs 35 ms in the used configuration, thus the frequency of the real-time tune measurements reaches up to 25 Hz. With fast FFT processor or with stored records and off-line processing equivalent rate above 500 Hz can be achieved. To improve the noise floor the spectra can be averaged. Programmable window selects the region of interest around the tune peak. Graphic and numeric display shows the tune as a function of time.

5 IMPLEMENTATION FOR MULTIBUNCH RING

In multibunch electron synchrotrons containing k bunches the fundamental frequency is $k * f_{REV}$. The betatron sidebands appear around its harmonics ($j * k * f_{REV} \pm q * f_{REV}$, $j = 0, 1, ..$). In case of unevenly filled bunches further lines with double betatron sidebands appear in frequency intervals of f_{REV}.

For the tune measurement signal preprocessing electronics convert the spectrum into a lower frequency range corresponding with the single bunch spectrum. The main RF transposes the difference signal of a BPM. On the output of the mixer the betatron sideband of the fundamental bunch frequency appears between DC and $f_{REV} / 2$. Bandpass and lowpass filters exclude all higher frequency components to avoid aliasing. A divide by k counter generates the sampling frequency ($f_s = f_{REV}$). As the revolution frequency at electron accelerators is usually constant in the ramp, clock recovery from the sum signal is not necessary by all means.

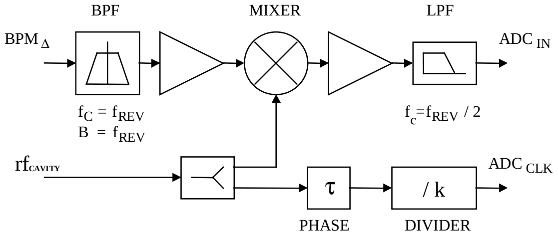

Figure 4: Blockdiagram of the preprocessing unit

Adjustable delay optimizes the sampling phase for the highest sensitivity. However the longitudinal oscillation is not separated without tracking clock. Fig. 4 shows the blockdiagram of the preprocessing unit.

6 CONCLUSIONS

Remarkable advantages: (1) Spurious peaks with constant frequency can easily be recognized and separated. (2) No frequency feedback on the excitation is necessary. (3) The acquisition time is short, nonlinear changes of the tune have less influence on the accuracy. (4) Because of the bunch-synchronous sampling, the FFT-spectra contain only the frequency range up to $0.5 * f_0$. (5) Due to the tracking clock the longitudinal and transversal spectra are separated. (6) The gated low level excitation causes no noticeable particle loss. (7) The method with some additional signal conditioning can easily be implemented at multiple bunch machines.

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