Broadband FFT Method for Betatron Tune Measurements in the Acceleration Ramp at COSY-Jülich

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Abstract. A method for measurement of betatron tune without the need for feedback-driven excitation has been developed at COSY. A bandlimited broadband noise source was used for beam excitation. The transverse beam position oscillation was then bunch-synchronously sampled and digitized with a high resolution ADC. The Fourier transform of the acquired data represents immediately the betatron tune. A functional description of the measurement system and the evaluation of the measured data are presented.

INTRODUCTION

The cooler synchrotron and storage ring COSY, with a circumference of 184 m, 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, a magnetic impulse kicker or a broadband stripline exciter can be used. The 50W-stripline electrodes are mounted azimuthally in 45^0-positions; therefore, excitations in the diagonal direction are also possible and are useful, for example, to observe horizontal and vertical tune changes at the same time in one spectrum during beam optimization procedures. The mode of excitation and the strength can be automatically set. Beam position monitors (BPM) with low noise broadband amplifiers deliver signals proportional to the beam response on the excitation. The bunch-synchronous pulse, necessary for the sampling, is derived from the BPM-sum signal of the same BPM.

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

$$f_\beta^n = n * f_0 \pm Q * f_0 = (n' \pm q) * f_0 \qquad (1)$$

where n and n' are integers and q is the fractional part of the tune.

MEASUREMENT CONFIGURATION

Via the stripline unit, resonant excitations of coherent betatron oscillations in the horizontal and vertical directions can be performed by means of a broadband white noise source with fixed cutoff frequencies. The betatron oscillation appears as an amplitude modulation of the beam position, causing bunched beam double sidebands around each harmonic of the revolution frequency and also around DC in the frequency spectrum. The frequency range of the noise source always covers at least one betatron sideband at the fundamental harmonic in the whole ramp without frequency feedback. A low-noise preamplifier and gain-controlled stage amplify the sum and difference signals of a beam position monitor. The gain-controlled amplifier for the difference signal ensures an optimal use of the 14-bit ADC. The sum signal is the reference for a clock generator. Figure 1 shows the block diagram of the FFT tune meter.

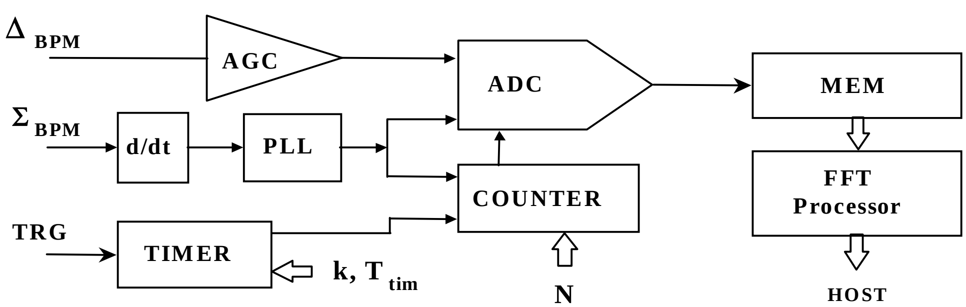

FIGURE 1. Block diagram of the FFT tune meter.

With proper signal processing, the clock generator tracks the bunch peaks and also the synchrotron oscillation. The bunch-synchronous clock pulse produces positive edges at the bunch peaks. For investigation of the synchrotron oscillations, a signal proportional to the synchrotron oscillation can be derived from the tracking circuitry of the clock generator. The peak value of the difference signal, proportional to the beam position, is sampled by means of a fast S&H circuit under control of the bunch-synchronous clock. A fast, high-resolution ADC digitizes the output in each clock period. This configuration combines the functions of a synchronous demodulator and a frequency normalizer. The magnitudes of the samples carry the position changes and the betatron oscillation; the sampling frequency is always equal to the revolution frequency. Due to the bunch-synchronous sampling, the frequency components of the synchrotron oscillation are suppressed. The sampled data, therefore, contain mainly the frequency component of the first sideband with

$$f_{\beta,n'=0} = q*f_0 < 0.5*f_0. \quad (2)$$

DATA PROCESSING

Performing the discrete Fourier transformation of N sequentially acquired samples gives:

$$S\left(\frac{m}{NT}\right) = \sum_{n=0}^{N-1} s(nT) * e^{-j(2\pi nm)/N} \quad , \tag{3}$$

where T is the time interval of the samples, $s(nT)$ the n-th sample of an array consisting of N samples, and $S\left(\frac{m}{NT}\right)$ the m-th Fourier component at $f_m = \frac{m}{NT}$.

Due to the bunch-synchronous sampling, the frequencies of the resulting data are normalized to the revolution frequency. Oscillations appear as a peak in the normalized frequency domain. The value N must be properly chosen because it determines the frequency resolution of the FFT-spectra (equal to $1/NT$ with $1/T = f_{sample} = f_0$). As shown above, the bigger the samples in the array used for evaluation, the higher the frequency resolution and consequently the accuracy of the q-measurement. The lowest normalized frequency is zero (DC component); the highest according to Nyquist is $f_{sample}/2$, the corresponding tune range is between 0 and 0.5.

Because the revolution frequency is used as the sampling frequency, it follows that:

$$q * f_0 = f_q \Leftrightarrow f_{m'} = \frac{m'}{N} * f_0 \text{ therefore } q = \frac{m'}{N} \; (0 < q < 0.5 \text{ or } 0 < 1-q < 0.5). \tag{4}$$

The acquired data blocks with N data words each are transformed by the FFT resulting in frequency spectra with $N/2$ datapoints.

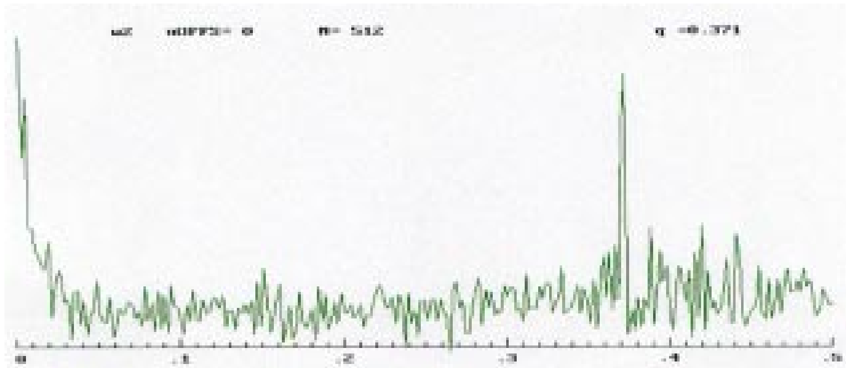

FIGURE 2. Betatron line in the normalized frequency domain.

Figure 2 shows a sideband line in the spectrum; the normalized frequency corresponds to the fractional betatron tune value. The spectra subsequently acquired with equidistant time intervals and displayed with frequency axis vertically, show the tune versus time in the acceleration ramp (Fig. 3).

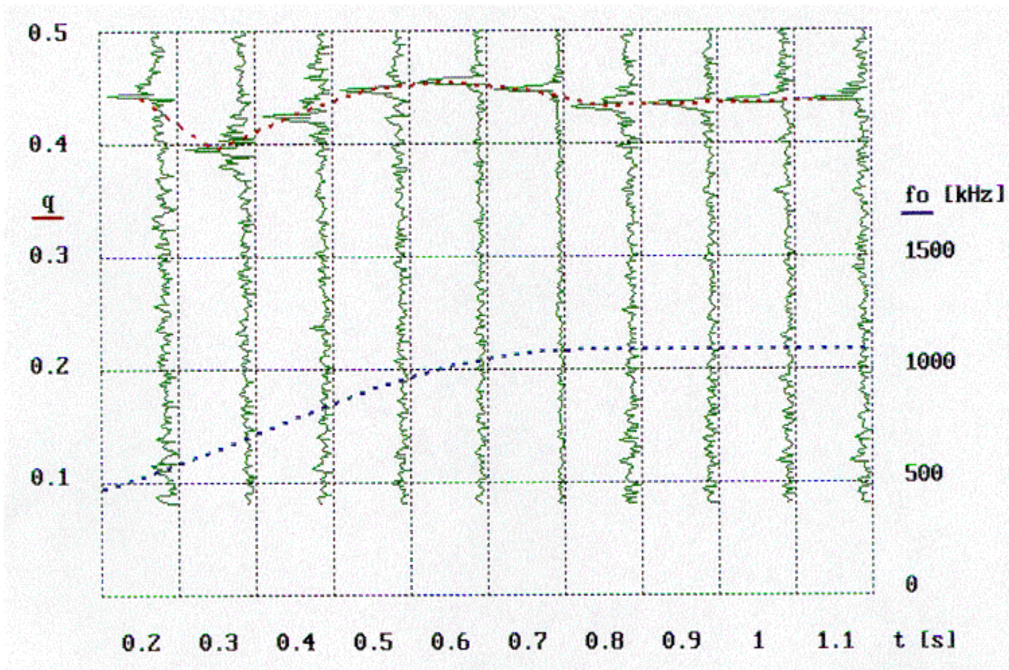

FIGURE 3. Display of a tune measurement in the acceleration ramp consisting of ten FFT- spectra. The sideband lines are clearly seen. The frequency ramp is shown in the lower part.

In the normalized frequency domain, the fractional tune value is directly shown. The frequency f_m of the m-th datapoint (m = 1,..,N/2) is $f_m = m/NT$, with $1/T = f_{sample} = f_0$. If f_m' is the frequency of the sideband, it follows $f_m' = m'/N*f_0$, and, since $f_m' = q*f_0$, then $q = m'/N$.

TIMING

The data are taken in blocks of N data words each and are stored sequentially in memory. To start the measurement, the COSY timing system triggers internal timing logic which, in turn, generates k timing pulses with constant time delay. The number k of timing pulses and their delay must be properly chosen in order to obtain a tune measurement time overlapping the total acceleration ramp time as desired. In the data acquisition cycle, $k*N$ samples corresponding to k tune value measurements are acquired. The acquisition time for a tune resolution of 1/1000 is less then 2 ms.

CONCLUSIONS

Several advantages of this method are remarkable. Spurious peaks with constant frequency can easily be recognized and separated because their time dependence shows an inverse normalized frequency behavior to the frequency ramp. The single measurements in the ramp are independent from each other. Therefore, an unsuccessful measurement does not disturb the results from the good data. The acquisition time is short so nonlinear changes of the tune have less effect on the accuracy. Because of the bunch-synchronous sampling, the sampling frequency corresponds to the fundamental frequency f_0 of the pulse spectrum and the FFT-spectra contain only the frequency range up to $0.5*f_0$. Consequently, all higher order sidebands are converted to the same (the first) sideband and all harmonics of the revolution frequency to DC; therefore, no disturbing aliasing components appear in the spectra. The sampling clock tracks the synchrotron phase oscillations of the beam; therefore, longitudinal and transverse spectra are separated .

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