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ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

DEVELOPMENT OF TOOLS FOR REAL-TIME BETATRON TUNE MEASUREMENTS AT THE NUCLOTRON

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A betatron tune measurement system was developed and tested at the Nuclotron. White noise and chirp signals were used for transverse beam motion excitation. A custom FlexRIO digitizer module was developed which provides excitation signal generation for kicker electrodes and real-time signal acquisition from pickup electrodes. A high-resolution FFT algorithm was implemented inside an NI PXI FPGA module, connected to digitizer. The measurement system is integrated with the NICA control system based on the TANGO Controls. Results and tests performed with the Nuclotron beam are presented.

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INTRODUCTION

One of the key parameters of the synchrotron accelerator is the betatron tune. It is defined by the arrangement and strength of the focusing and defocusing quadrupoles (FODO lattice) around the ring. The ideal particle will follow a particular trajectory, which closes on itself after one revolution — the closed orbit. The real particles perform oscillations around the ideal closed orbit. These transverse oscillations are called betatron oscillations, and they exist in both horizontal (X) and vertical (Z) planes. The number of such oscillations per one beam turn is called betatron tunes — Q_x and Q_z. If an integer part of the tune agrees with the accelerator model predictions, large optics errors can be ruled out, such as dipole errors, which lead to the integer resonances. The fractional part of the tune have a strong effect on a beam lifetime and emittance, since quadrupole errors lead to resonances at half-integer Q values, sextupole fields excite resonances at third-integer Q values, and so on [1]. That is why an accelerator working point (Q_x, Q_z) has to be chosen at a reasonable distance from the resonance lines on the calculated diagram of resonances [2]. Measuring and controlling the betatron tunes can improve the beam lifetime and reduce the beam loss during acceleration. In the following, the fractional part of the tune will also be denoted by Q.

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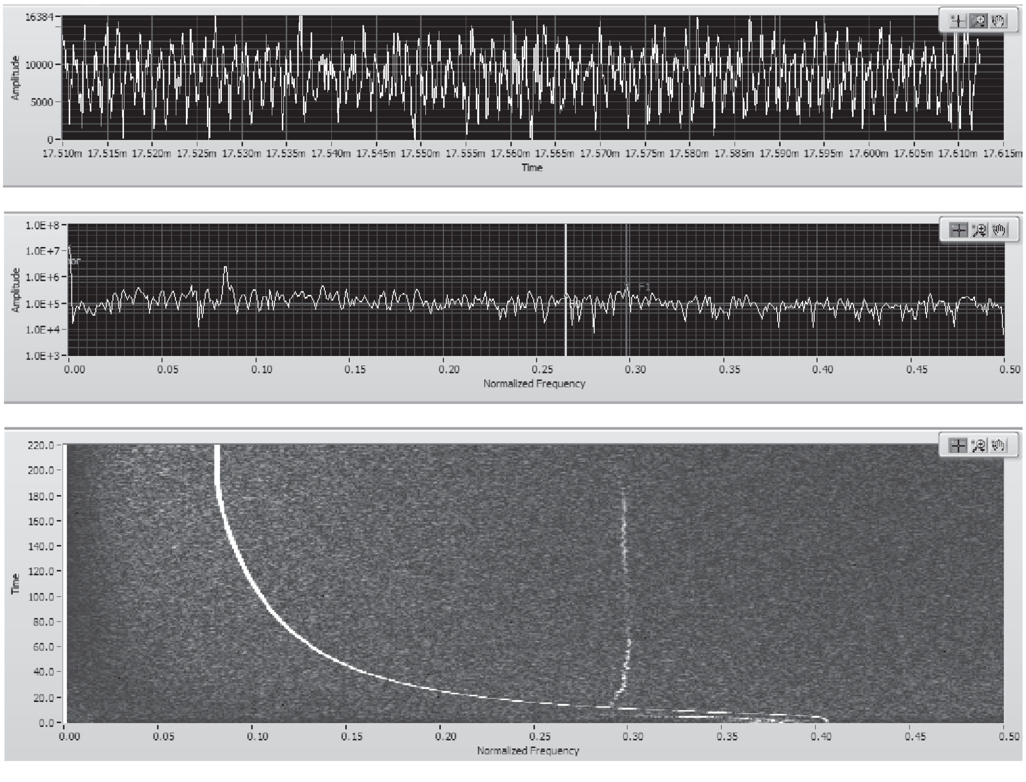
MEASUREMENT METHODS

Two approaches to measure the fractional part of the betatron tune was implemented and tested. The first method to measure the Q is to excite transverse beam motion and to detect the transverse beam position over a number N of successive turns [3]. The fractional part of the betatron tunes (Q_x, Q_z) can be calculated as the ratio of the betatron oscillation frequency (f_β) and the particle revolution frequency (f_{rev}):

$$Q = f_\beta / f_{\text{rev}}.$$

Thus, to calculate Q value, we must know the exact values of the revolution frequency (f_{rev}) and the betatron oscillation frequency (f_β) at the same time. The excitation signal can be selected from white noise and a chirp — signal in which the frequency increases (“up-chirp”) or decreases (“down-chirp”) with time. The power density of the detected signal is computed via a Fast Fourier Transformation (FFT), and the betatron tune (f_β) is identified as the frequency with the highest amplitude peak. The frequency resolution of the FFT is the ratio of sampling rate to the size of the data frame. The maximum FFT error due to the



Q_x measurement during acceleration with mixed constant frequency 50 kHz from the signal generator (bright track on the left of the figure), the ADC sampling frequency is equal to the beam revolution frequency, excitation signal is white noise, frame size is 1024 samples, measured value of Q_x is 0.283

discreteness of the frequency steps is equal to [4]

$$\Delta f = f_s/2N,$$

where N is total number of samples in the data frame; f_s is ADC sampling frequency.

For example, with a constant sampling frequency of 10 MHz and a frame length of 8192 samples, the frequency resolution is approximately 1.2 kHz. The measurement system accuracy was improved by data windowing (Hamming window, which has a side-lobe level — 42 dB) before the FFT calculation and parabolic interpolation of the signal in the vicinity of the resonance peak. When the magnitude of the frequency error is expressed in units of Δf, the largest error with the interpolation is 6.8% of Δf [4]. Thus, frequency resolution is increased 15 times after data windowing and interpolation, so to get the same frequency resolution of 1.2 kHz with $f_s = 10$ MHz only 1024 samples are used.

The second method to measure the Q is to provide the ADC sampling with a beam revolution frequency. In this case the resonance peak position obtained by the FFT is the fractional part of Q with no additional computations. The beam revolution frequency $(f_{\rm rev})$ at the Nuclotron changes nonlinearly from 125 kHz to 1.2 MHz during acceleration. The accelerating frequency harmonic number is 5. The results are shown in the figure.

THE MEASUREMENT SYSTEM IMPLEMENTATION

A custom FlexRIO digitizer module was developed for a real-time signal acquisition and generation of an excitation signal. Vendor ID 0xAB66 was obtained from National Instruments for production of the FlexRIO modules at JINR. In the following, FlexRIO digitizer module will be denoted by Digitizer. This module is an 8-layer PCB board with two AD9244 (14-bit, 65 MSPS ADC), one DAC904 (14-bit, 165 MSPS DAC), one analog input for the beam revolution frequency, which is taken from RF system, one analog input for synchronization with the start of injection. All inputs and outputs are galvanically isolated using the RF transformers (ADT1-6T). The ADCs are used to digitize an amplified signal, which are coming from pickup electrodes, mounted in X and Z planes. DAC is used to output an excitation signal. To excite transverse beam oscillations, scanning frequency (chirp) and band-limited white noise were used. A chirp signal is generated by a direct digital synthesis (DDS) in a predetermined frequency range and scanning time. DDS is implemented in the FPGA (Virtex-5) and a generated signal is output from the FlexRIO Digitizer DAC. The DAC sampling frequency is filtered from the output signal by a fourth-order elliptic low pass filter. Further, an excitation signal is amplified by the AR 800A3A RF amplifier and then applied to the kicker electrodes via impedance transformers.

FlexRIO Digitizer module has a direct access to the I/O ports of the FPGA. The FlexRIO digitizer module is inserted into 132-pin connector of the NI PXIe-7962R FPGA module for the PXI system crate NI PXIe-1082 which is 8-slot 3U PXI Express chassis with a 1 GB/s per-slot back-plane data bus. The PXI system crate also contains necessary additional modules such as Tegam-4040A (two-channel differential amplifier) and NI PXIe-8135 (high-performance Intel Core i7-3610QE processor-based system controller).

Windowing of the input signals, interpolation and FFT algorithms are implemented in the FPGA. The signal processing (FFT calculation) starts simultaneously with the start of the input data accumulation and ends at the same time with the end of the data accumulation. The resources of the PXI system controller (PXIe-8135) are used for distributed control system based on TANGO Controls software toolkit [6] in which devices are controlled and monitored in a local distributed network. The signals from the two ADC channels and the FFT results are stored in the internal memory (512 MB DDR2) of the FPGA module. Built-in memory allows one to record the digitized data with a sampling frequency of 10 MHz from two 14-bit ADC channels for up to 4 s and the results of the FFT. After the end of the data accumulation, results are transferred to the system controller PXIe-8135 via the DMA channel and displayed via remote TANGO Controls client application (figure). The data transfer takes 0.9 s.

CONCLUSIONS

The betatron tune measurement system was successfully tested during the 51st run of the Nuclotron. The implementation of a high-resolution FFT algorithm in an FPGA has allowed the real-time acquisition of the betatron tune. The implementation of a digital frequency synthesizer (DFS) inside the FPGA module allowed one to produce chirp and white noise excitation signals. The further improvements are planned to increase the sensitivity of the measurement system and use diode detection technique which can improve the tune measurement resolution by one order of magnitude [7].

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