DEVELOPMENT OF HIGH SPEED DIGITIZER MODULES FOR REAL-TIME BETATRON TUNE MEASUREMENTS AT THE NUCLOTRON

1. 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 in 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.

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}):

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

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 a 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 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_{rev}) at the Nuclotron changes non-linearly from 125 kHz to 1.2 MHz during acceleration. The accelerating frequency harmonic number is 5. In this case only 128 samples are enough for measurement of Q with the accuracy of 0.001 [4].

The core of the Q-measurement system [1] is control system based on PXI chassis (Figure 1). It contains digitizer module which is used to convert amplified signal from pick-up electrodes into digital representation. 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 of the FPGA module. A FlexRIO digitizer module has direct access to the input-output ports of an FPGA.

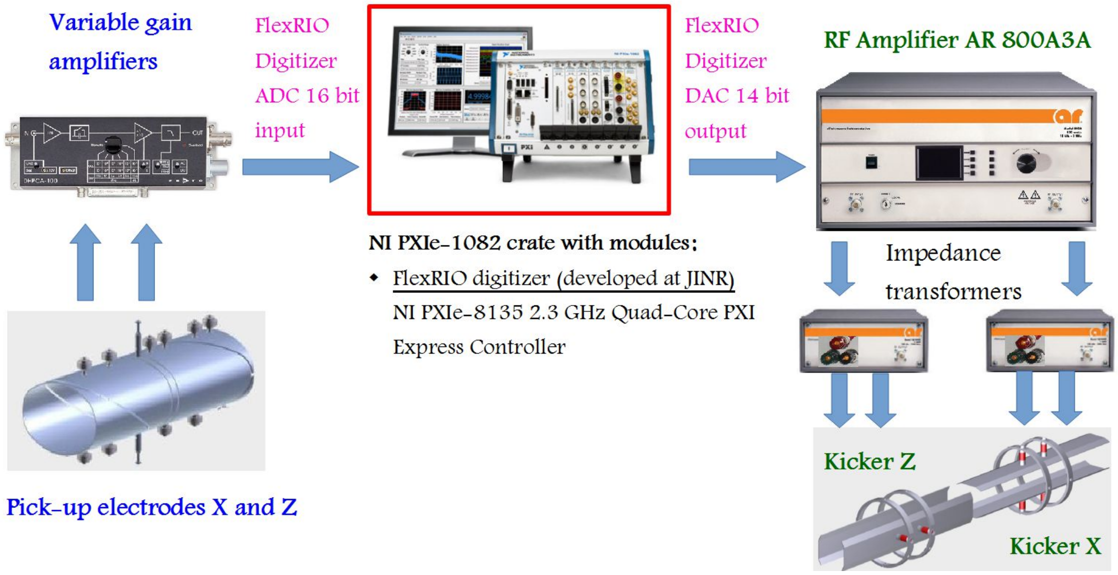


Figure 1. Q-measurement system

All components of the digitizer module are controlled by FPGA logic created with the LabView FPGA tool [5]. The connection of an FPGA module and the digitizer is shown in **Error! Reference source not found.**.

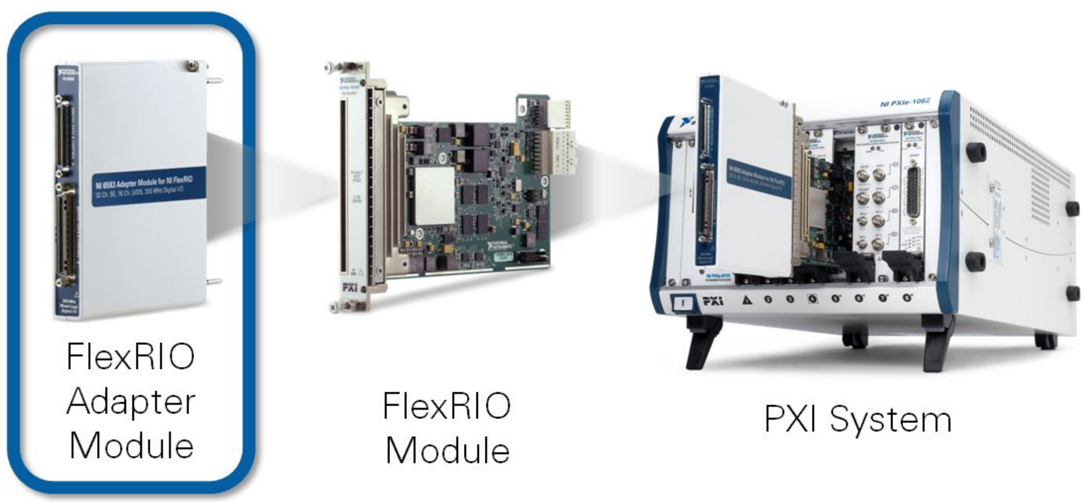


Figure 2. FPGA PXI module and FlexRIO digitizer

The first developed 14-bit FlexRIO digitizer (Figure 3) was used for calculation of Q as the ratio of the betatron oscillation frequency (f_β) and the particle revolution frequency (f_{rev}): $Q = f_\beta / f_{rev}$. To increase the accuracy and to be able to measure Q at a low beam intensity, a new 18-bit digitizer was developed (Figure 4).

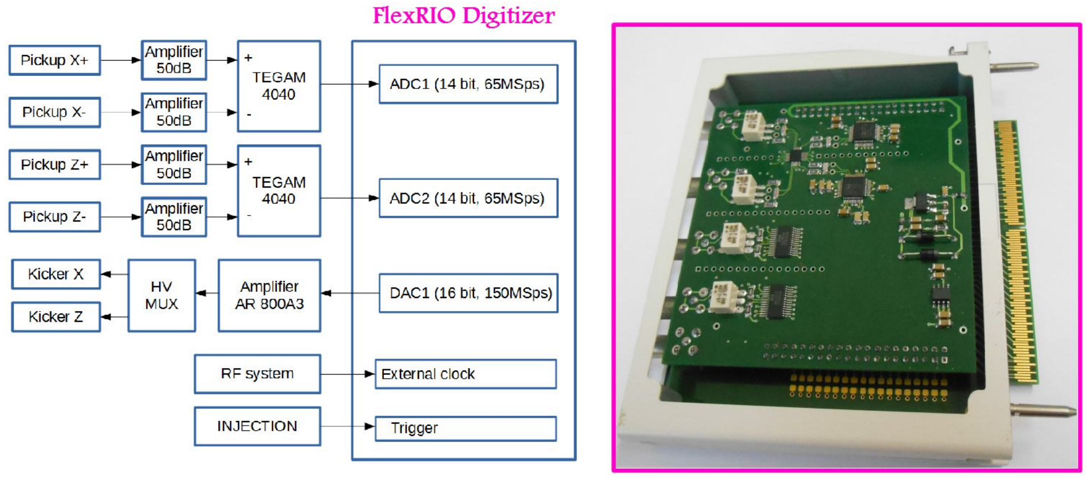


Figure 3. 14-bit FlexRIO digitizer module

The new 18 bit FlexRIO digitizer module is a custom developed at JINR 8-layer PCB board, which is compatible with the NI PXIe-7976R PXI Express module. It has a Kintex-7 XC7K410T FPGA onboard, which calculates a high resolution FFT in real time. The new digitizer module is shown in **Error! Reference source not found.**4.

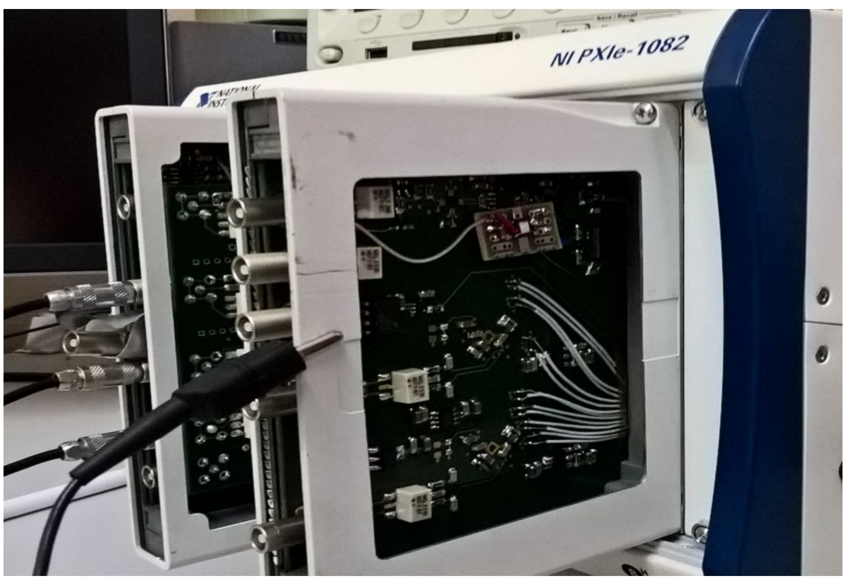


Figure 4. 18-bit digitizer module

To provide signals for FFT algorithm two 18 bits ADC are used. One ADC channel is used for Q_x measurement and the second one is used for Q_y. Each ADC is an 18-bit, 5 MSPS, charge redistribution successive approximation (SAR), analog-to-digital converter – AD7960. The AD7960 digital interface uses low voltage differential signaling (LVDS) to enable high data transfer rates and operates at a high frequency of 200 MHz which eliminates the need for anti-aliasing filters. A conversion can be initiated asynchronously to provide the ADC sampling with a beam revolution frequency. This approach simplifies and speed-up Q measurement because the resonance peak position obtained by the FFT represents the fractional part of Q with no additional computations.

To measure the exact value of the revolution frequency a high resolution time-to-digital converter is used – TDC-GP22. It can measure the period within 90 ps accuracy. To provide a low jitter and noise-free signal for TDC a very fast comparator with LVDS compatible output was used – ADCMP605. It has an adjustable hysteresis feature that significantly improves accuracy and stability and gives an opportunity to adjust comparator switch level.

An optically coupled high speed gate HCPL-2631 with propagation delay of 45 ns is used for synchronization with the start of injection to give a start for data accumulation. A high-speed 14-bit resolution DAC (DAC904) is used for an excitation signals generation (white noise and frequency scan) which are used to excite transversal beam oscillations.

The new 18-bit digitizer allows tracking the Q during acceleration cycle with low beam intensity 10^8 particles (Figure 5). New Q-measurement system is designed for measuring Q at compact superconducting synchrotrons with a beam revolution frequency up to 10 MHz, such as JINR NICA Booster and Nuclotron.

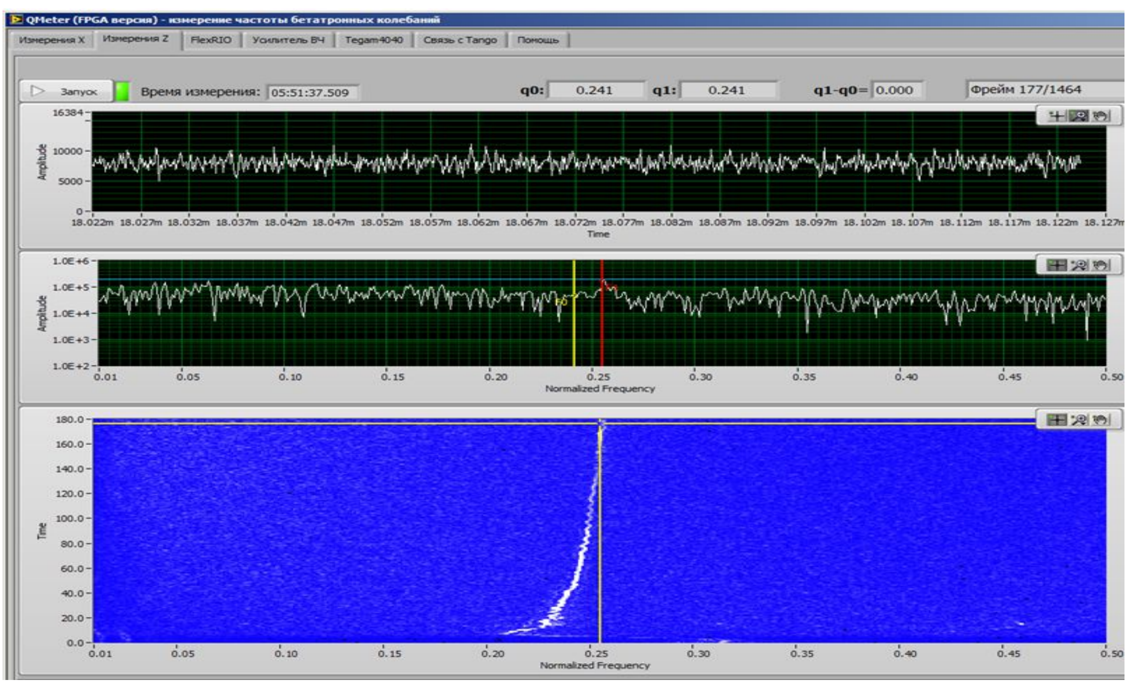


Figure 5. Q_x tracking during beam acceleration

2. STUDENT PRACTICE

1. Students will be given theoretical information about the operation of superconducting synchrotron accelerators, as well as the betatron tune and the importance of its measurement.
2. Students will be given information about how to develop high speed electronics - PCB for NI FlexRIO digitizer module, LVDS interface for 18-bit ADC using VHDL. All project files, VHDL codes and development tools will be provided to students for quick start in developing their own electronics.
3. Students will be given information about how to develop Tango Device servers, using Python and PyQt for building large distributed control systems, such as the NICA project control system.
4. Students will have a hands-on experience of soldering SMD components.
5. Students will be able to design analog filters and measure their frequency and phase response.
6. Students will have an excursion to the Nuclotron.

3. SKILL REQUIREMENT

This practice is suitable for beginners in the field of electronics development.

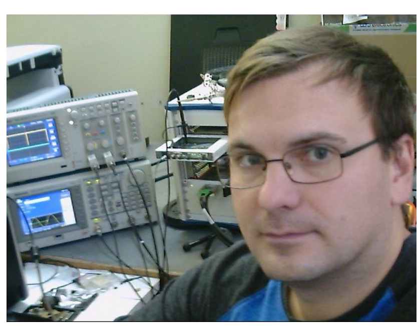
4. PROJECT SUPERVISOR

Dmitrii Monakhov

Lead Engineer

VBLHEP

E-mail: monahov@sunse.jinr.ru



5. REFERENCES

1. *F. Zimmermann*. Measurement and Correction of Accelerator Optics. Stanford Linear Accelerator Center (SLAC), Stanford University, Stanford, CA 94309, USA, SLAC-PUB-7844, June 1998.
2. *G. Trubnikov, I. Meshkov, A. Butenko, G. Khodzhibagiyan, A. Sidorin*. NICA collider complex: challenges and perspectives. Status of the Project. JINR-SAR Round Table, 05 July 2015.
3. *A. Boccardi, M. Gasior, R. Jones, K. Kasinski, R.J. Steinhagen*. The FPGA-based continuous FFT tune measurement system for the LHC and its test at the CERN SPS. European Organization for Nuclear Research, CERN – AB Department, CERN-AB-2007-062, Geneva, Switzerland, August 2007.
4. *M. Gasior, J.L. Gonzalez*. Improving FFT frequency measurement resolution by parabolic and gaussian interpolation. European Organization for Nuclear Research, CERN – AB division, AB-Note-2004-021 BDI, Geneva, Switzerland, February 2004.
5. NI LabVIEW FPGA Module: http://www.ni.com/labview/fpga
6. TANGO Controls: http://www.tango-controls.org
7. *M. Gasior, R. Jones.* High Sensitivity Tune Measurement by Direct Diode Detection // CTWA01, Proceedings of DIPAC 2005, Lyon, France.