# Software and hardware complex for monitoring the ion beam parameters of a particle accelerator

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**Abstract.** This paper presents the development of an integrated system for monitoring the position of the ion beam in a particle accelerator. The effect of external disturbances and the imperfection of the accelerators themselves lead to the distortion of the ion beam trajectory in a cyclotron; therefore, constant monitoring and correction of the beam position is necessary. To control and correct the distortion of the ion beam trajectory in a cyclotron, an electrostatic sensor based on a pickup electrode is used as a meter. One of the features of the developed meter is that the estimation is carried out according to the second harmonic of the signal, allocated on a band-pass filter. This is due to the fact that during the accelerator work a large amount of noise is induced on pickup electrodes and the noise level at the fundamental frequency is high. The hardware and software complex converts the measured data obtained from the sensors, such as the transverse distribution of the beam energy, the beam current and the coordinates of its center of mass into an electrical signal, followed by their sampling in an analog-to-digital converter and the transmission of the measurement results through standard communication protocols and further processing in the LabView software. Using the received signals, the beam parameters such as the length of the ion bunch, the vertical beam position, and the acceleration phase are calculated for the corrector.

## 1. Introduction

Accelerators of charged particles such as cyclotrons, microtrons, synchrotrons, colliders are the main tool of high energy physics — the science of the fundamental properties of matter [1]. Countries all around the world put into operation large number of particle accelerators of various types [2].

The field of application of accelerators is extremely wide. Ion irradiation is necessary in such industries as materials science, chemistry, microelectronics, nanotechnology, biology, and medicine [3, 4].

Extreme requirements are imposed on the quality of the beams in modern accelerators; therefore, the efficient operation of accelerator complexes is almost unthinkable without precision systems that allow timely correction of the accelerator parameters in accordance with the measurement results to ensure the required beam parameters [5].

In a resonant cyclic accelerator (cyclotron) of nonrelativistic heavy charged particles (protons, ions), particles move in a constant and uniform magnetic field [6, 7].

To accelerate them a high-frequency electric field of constant frequency is used. Heavy accelerated particles are injected into the chamber near its center, then they continue to move in the cavity of two extended half cylinders (dees), which are placed in a vacuum chamber between the poles of a strong

electromagnet. The uniform magnetic field of this electromagnet bends the particle trajectory and thus the acceleration of moving particles occurs at the moment when they are in the gap between the dees, where they are affected by the electric field created by the electric generator of high-frequency (equal to the particle revolution frequency inside the cyclotron – cyclotron frequency) where they always get at the same instant, since at nonrelativistic velocities it does not depend on the particle energy [6, 7]. Particles in the horizontal plane are automatically focused in a uniform magnetic field. Vertical focus is due to the non-uniformity of the electric field in the accelerating gap. At the entrance of the accelerating gap, the particle will experience a push toward the median plane by the vertical component of the edge electric field when it is shifted vertically from the median plane. Due to the finite displacement of the particle, the push at the output will be of lesser strength and of opposite sign. Additional focusing occurs on the outer radius of the cyclotron, in both coordinates due to the linear field gradient, where the magnetic field decreases [8].
For a relativistic particle, the revolution frequency depends on energy and the charged particles cannot be accelerated to high energies, which is a disadvantage of the cyclotron [8, 9]. Due to impaired synchronism, particles cease to accelerate, since they get in an accelerating gap in the wrong phase.

## 2. Problem Definition

Monitoring the parameters of a charged particle beam is an extremely important task during the operation of accelerator devices. Correction of the trajectory and transverse distribution of particle beam energy is a complex task requiring non-standard solutions and the use of a complex of modern control methods. The efficient operation of accelerator systems is virtually impossible without accurate and reliable beam diagnostic systems [10].
Beams of charged particles in accelerators are grouped, focused, accelerated, cooled, transported from one part of the device to another and are carried out in conjunction with the coordinated operation of precision such electromagnetic devices as rotary dipole and focusing quadrupole magnets, electrostatic deflecting devices, accelerating high-frequency resonators and other [11]. Since modern particle accelerators are high-tech devices, the level of their components is close to the limit of technical and economic production capabilities [12].
The technical shortcomings of accelerators as well as the effect of external disturbances, lead to the fact that the particle beam motion in a real accelerator differs to a certain extent from the calculated motion, for which it is necessary to constantly control the beam parameters [10].

## 3. Solutions

The main task is to ensure the required quality of the ion beam, for which the accelerator parameters are corrected according to the final effect of changing the measured beam parameters in the right direction [12]. Beam correction is conducted by affecting the focusing quadrupole magnets using an intelligent automatic control system [3, 13].
The designed software and hardware module for controlling the focusing of charged particle beams in the accelerator will provide the ability to constantly adjust the parameters of the accelerator according to the measurement results. This module is designed to obtain data on the state of the beam after it is removed from the accelerator device, such as: beam current, coordinates of the center of mass, transverse distribution of particles.
Particle beam parameters are measured by sensors — devices that interact with bunches of charged particles. Extremely strict requirements are imposed on such sensors [2, 5, 14]. First of all, it is necessary that the sensors are as transparent as possible, which means that they should not degrade the parameters of the beam and do not affect its intensity, operate in a wide range and are of high precision. [15-17]
The entire spectrum of beam control sensors can be divided into groups.
Physical principles underlying the operation of the sensor:
– contact sensors that directly interact with the beams [2, 18];
– optical sensors that detect radiation in the visible, ultraviolet or x-ray ranges [19-22];

– electromagnetic sensors, signals of which are generated by an electromagnetic field induced by the beam [18, 23].

After considering the principles of operation, the devices and the main characteristics of the sensors of all types, a selection was made. To measure the distribution and focusing of a charged particle beam in an accelerator, an electrostatic detector was chosen [24]. The basis of such detector design is a thin wire electrode that moves perpendicular to the trajectory of accelerated particles. With each passage of the ion bunch through the wire, a charge arises on it due to the secondary emission of electrons. The current at the electrode will be proportional to the beam density in this section, since the speed of the wire electrode relative to the speed of the bunch is negligible [24].

An electrostatic sensor is a system of two conductors, one of which is a signal and the other (camera) is grounded [24]. The current in the signal conductor circuit is induced by the moving beam charges. A circuit containing the load resistance (at which voltage is generated) is the output of the sensor. Using the received signals, basic beam parameters are calculated, such as vertical position of the beam, acceleration phase, and length of the ion bunch [24].

## 4. Implementation

In our work, we use the detector consisting of two moving wire electrodes located perpendicular to each other. It is advisable to use the non-destructive testing method, where the time of flight of induced charged particles with the same microbunch is determined by recording signals from two pickup electrodes separated by a span base, for example [25–27].

The scheme of the electrostatic detector of the ion beam position (pickup electrode system) and a brief specification of the device are presented in Figure 1.

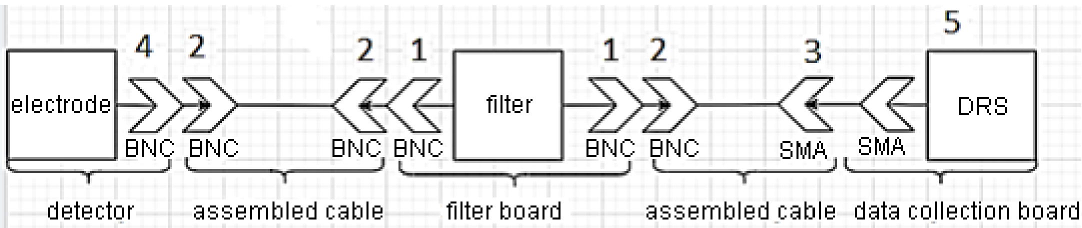


**Figure 1.** Diagram of electrostatic detector of the ion beam position

1) BNC connector; 2) BNC connector; 3) SMA connector; 4) BNC connector; 5) Data collection board PSI DRS4

To control the transverse coordinate in the accelerator chamber, a system is created using a set of pickup electrodes placed inside the cyclotron along the radius of the sector [28]. Electrical signals induced on pickup electrodes by the flying ion bunches are fed into the measurement system using coaxial cables. The system involves the use of 10 pairs of internal pickup electrodes shown in Figure 2.

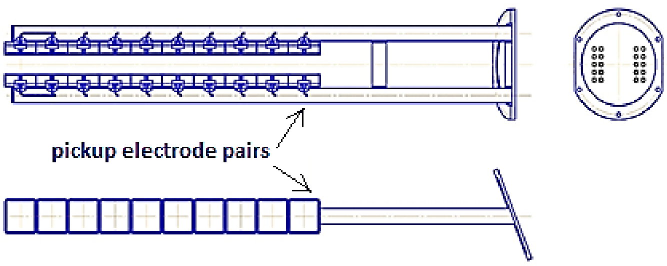


**Figure 2.** Pickup electrodes system

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An electrostatic position detector (pickup-electrode) provides the ion beam correction. Correction is performed automatically using a feedback system [29-32].
A large amount of interference is induced on pickup electrodes during the operation of the accelerator, therefore, to select the second harmonic of the signal we need, a band-pass filter should be applied [28].
The kr2445 filter with the following characteristics was designed and selected:
– Filter type: Band-pass;
– Center Frequency: 17.89 MHz;
– Min 3 dB Bandwidth: 6 MHz;
– Source & Load: 50 Ω.
The model of the printed circuit board for the filter was made in the 3D modeling software environment.

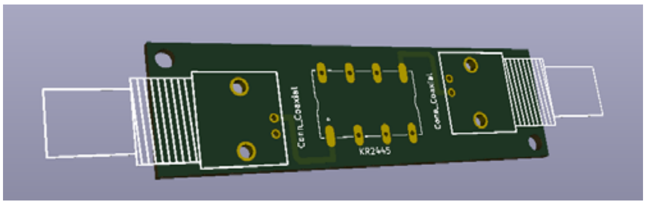


**Figure 3.** *3D*-model of the printed-circuit board for the kr2445 filter

In order to mount the filter the printed-circuit board was fitted with RF-connectors of the BNC type (Figure 4).

**Figure 4.** Band-pass filter

After filtering, a twenty-channel (20ch) data acquisition system (Figure 5), built on an ADC (analog-to-digital converter) of the DRS type (Domino Ring Sample), was designed to read and analyze the received signals [33].

**Figure 5.** Overall view of the data collection system assemblage

The DRS microchip is a fully functional integrated circuit developed according to the PSI standard (Switzerland). It contains a 1024-cell switched-capacitor array (SCA) that can digitize eight analog signals at high speed (6 GSPS) and high accuracy (11.5 bits SNR) on a single chip [33]. The system consists of five DRS cards connected in parallel.

To measure the phase of the ion beam acceleration, synchronization of all ADCs involved in the data collection acquisition is necessary. In DRS 4 boards, this is achieved by connecting all Trigger and Clock connectors in series according to the diagram shown in Figure 6 [33].

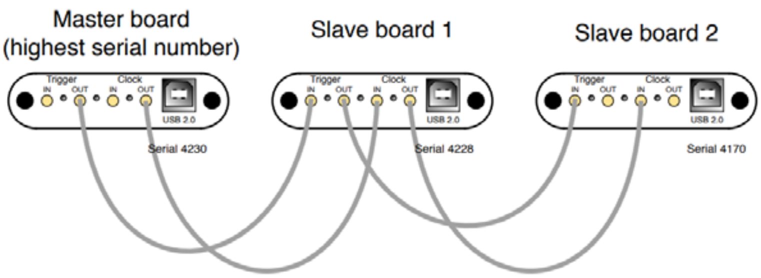


**Figure 6**. DRS connection diagram

## 5. Experiment

After assembling the data collection system prototype, a series of experiments was carried out to verify the performance of the device.

Test runs of measuring systems were made (Figure 7).

**Figure 7.** Data collection measuring system

A Tektronix signal generator was used to simulate pickup electrodes and noise.
A sinusoidal signal of 10 MHz was fed to the first channel. On channels 2–20, the signal identical to the first one was alternately fed to measure the phase displacement on each channel. As a result of the experiment, it was revealed that the signal sweep was 18 ns delayed with each subsequent board. To accurately measure the phase shift, the adjustment of the oscilloscope trigger by this value is needed.
After adjusting the trigger delay, the delay is compensated, which is visible on the oscilloscope screen (Figure 8).

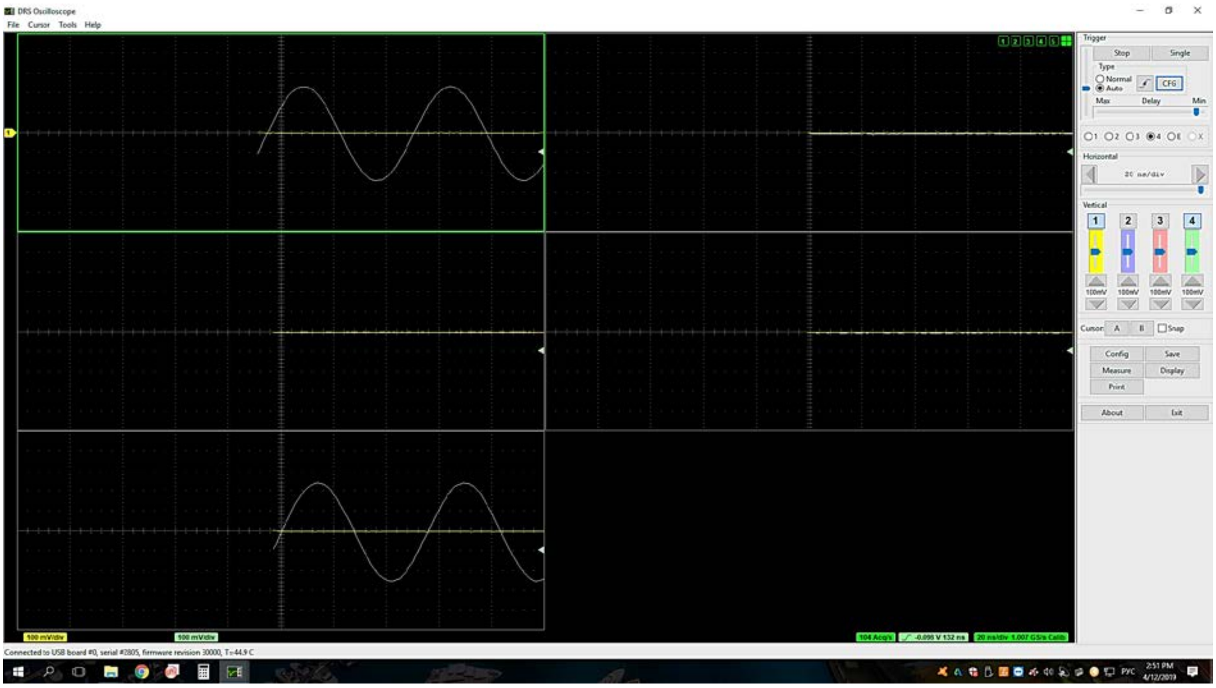

**Figure 8.** Oscilloscope screen after the trigger adjustment

The testing of the band-pass filter and the developed circuit board was also carried out. A signal of 18 MHz was fed to the filter input (which is its declared transmitted average frequency) and the amplitude was measured (Figure 9).

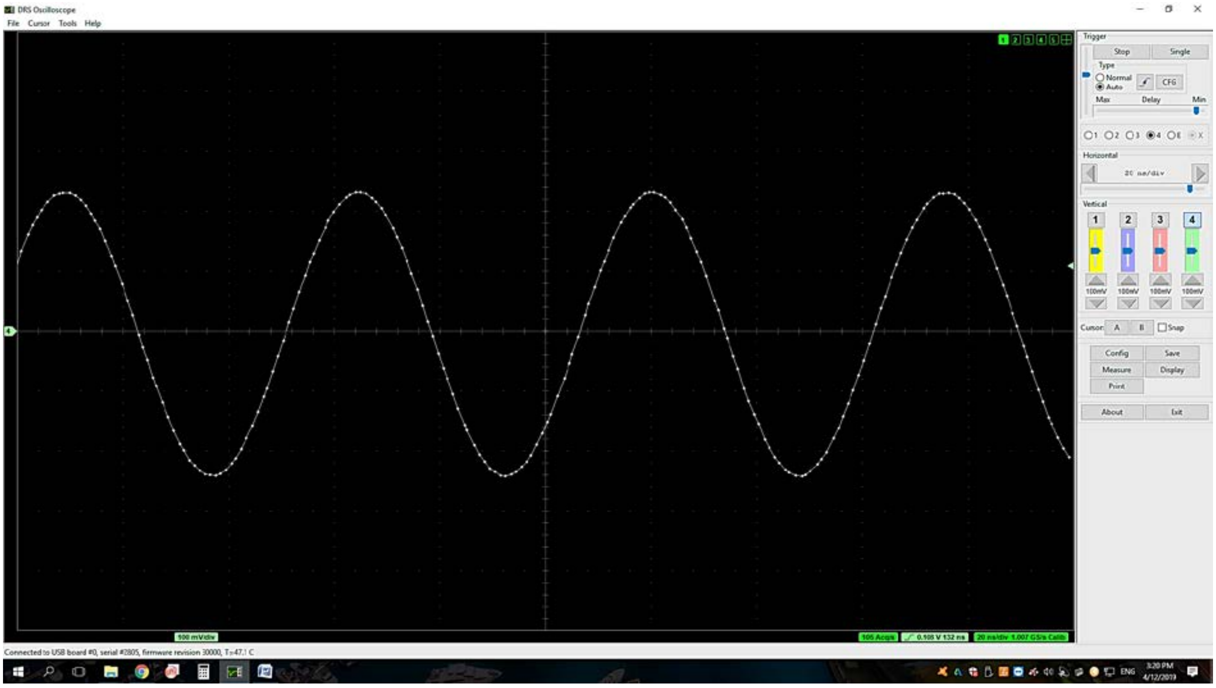

**Figure 9.** Signal amplitude at 18 MHz

Changing the frequency to 14 and 22 MHz leads to a double amplitude fading (Figure 10).

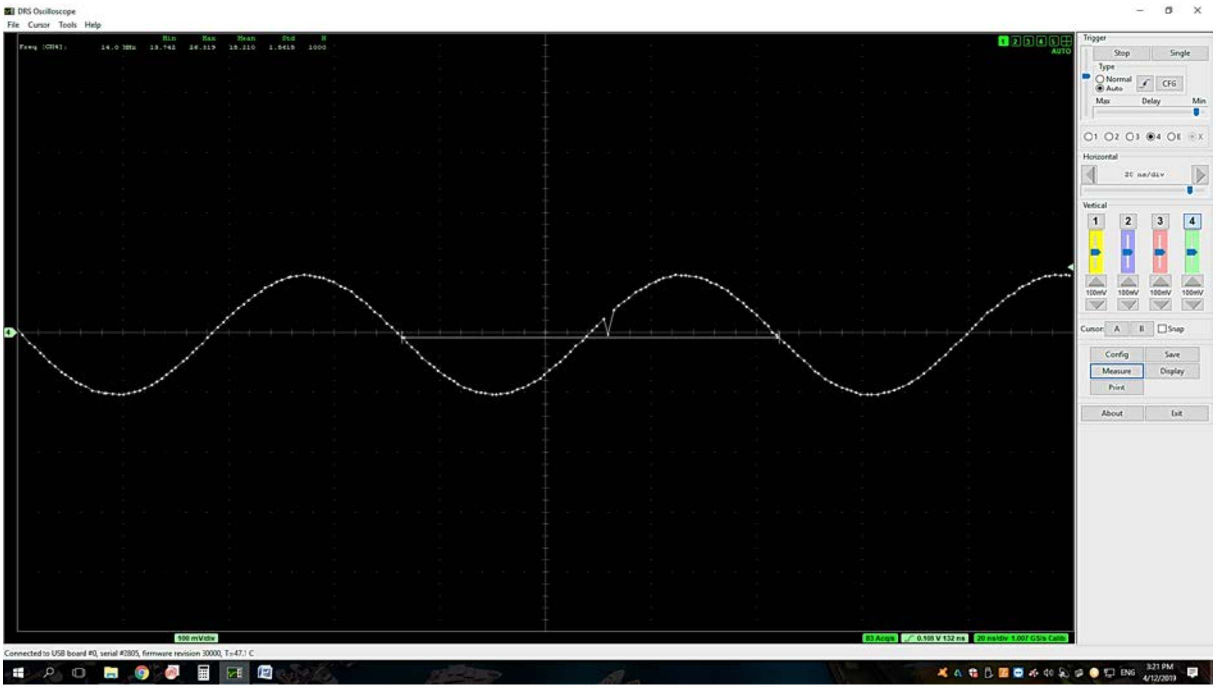

**Figure 10.** Amplitude fading

As a result of the experiment, it was proved that the developed measuring system works in accordance with its technical requirements.

## 6. Control

To control the complex hardware, a virtual device was created in the LabView software, which supports all the necessary functions and parameters for controlling the beam via a selected method [34].
Figure 11 shows the LabView interface used to configure and control the measuring complex, namely, it demonstrates the possibility to select various parameters of the ADC operation (e.g. the gain).

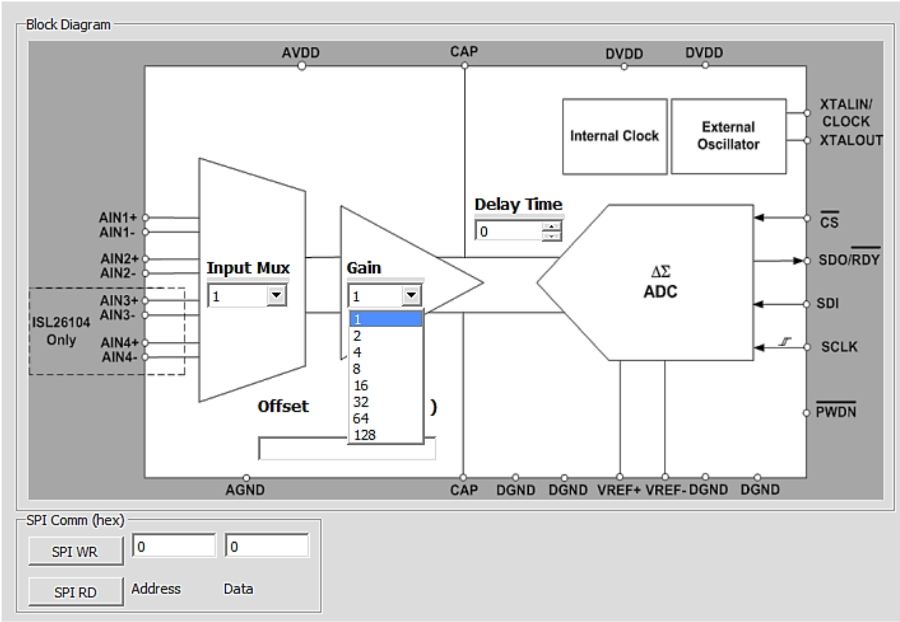


**Figure 11.** The measuring complex front panel

Figure 12 shows the implementation of one of the self-testing functions of the system, namely, the fast Fourier transformation for determining the noises and subsequent adjustment of their correction systems [36]. These adjustment tools include Blackman-Harris, Butterworth, Chebyshev filters [36].

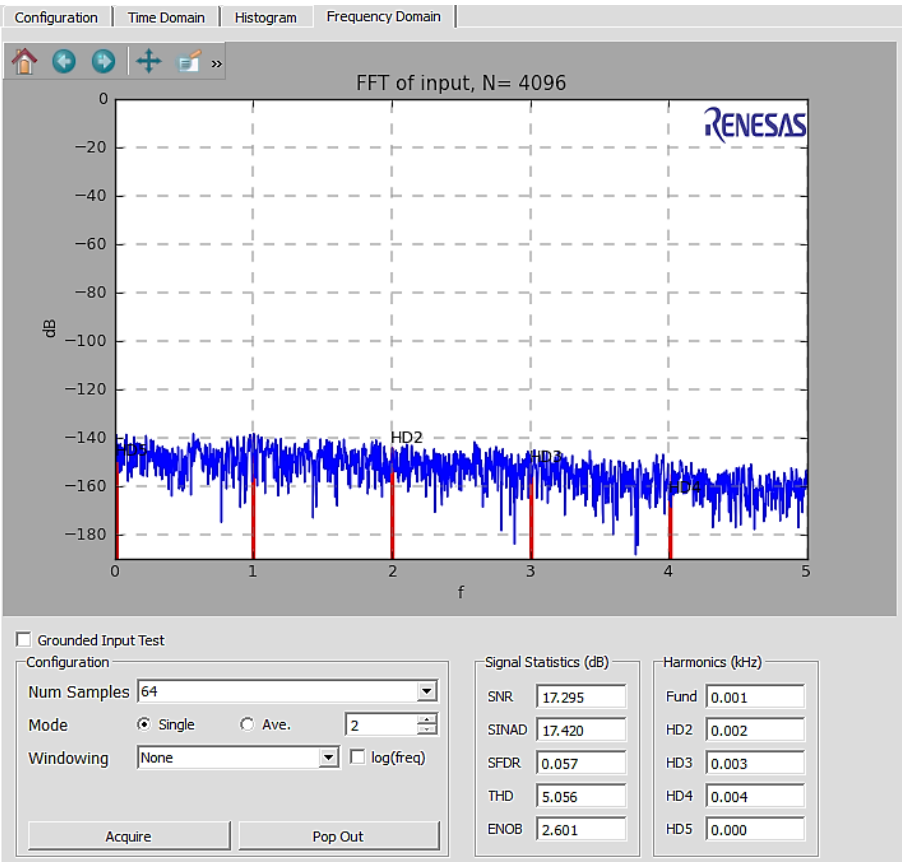


**Figure 12.** Fast Fourier transformation (sample N = 4096)

## 7. Conclusion

This work is devoted to the development of a system for monitoring the parameters of a particle beam in the output channel of an accelerator, optimization of the commissioning processes and adjustment of the parameters for capturing, injecting and removing the charged particle beams from the accelerating chamber. In the process of performing the work, a prototype of a control system for focusing the beams of charged particles was created and its tests were carried out in a particle accelerator.

As for the hardware part, a precision data collection system has been created; it has all necessary parameters of accuracy, data processing speed, radiation resistance and is compatible with crate automation systems designed for scientific research.

In order to read and analyze the received signals, a multi-channel data acquisition system was built. The system is built using an analog-to-digital converter of the Domino Ring Sample (DRS) type.

For reliable diagnostics of a beam of a resonant cyclic accelerator (cyclotron), a measuring data collection system was built on the basis of an electrostatic detector of the ion beam position. The system provides the ability to constantly adjust the accelerator parameters according to the measurement results. For the accelerator to work on pickup electrodes in interference conditions, a band-pass filter was developed with the second harmonic of the signal.

To manage the measuring complex and visualize the parameters of the measured particle beam, the software was developed on the base of the licensed software LabView-2017.

## 8. References

[1] Frank I and Ginzburg V 1945 Radiation of a Uniformly Moving Electron Due to Its Transition from One Medium to Another J. Phys. (USSR) pp 353–359

[2] Nikitin S, Anchugov O, Polunin A et al. 2006 *Record-high Resolution Experiments on Comparison of Spin Precession Frequencies of Electron Bunches Using the Resonant Depolarization Technique in the Storage Ring* (Proc. of EPAC Edinburgh, UK)

[3] Selivanov A and Fedotov M 2002 Digital television camera for real-time image *recording Proc. of IASTED Int. Conf.: Automation, Control and Information Technology. Novosibirsk*

[4] Bartolini R, Bazzani A, Giovannozzi M et al. 1989 *Tune Evaluation in Simulations and Experiments* (CERN SL/95-84 (AP). Geneva, Switzerland)

[5] Blinov V, Bogomyagkov A, Muchnoi N et al. 2009 Review of beam energy measurements at VEPP-4M collider *Nucl. Instr. and Meth.* V 598 No. 1 pp 23-30

[6] Ishkhanov B, Kapitonov I and Cabin E 2005 *Cyclotron. Particles and Nuclei. Experiment* (Publishing House of Moscow State University)

[7] Onishchenko L 2008 *Cyclotrons Physics of Elementary Particles and Atomic Nucleus* 39 vol **6** pp 1843-1897

[8] Craddock M 2007 *An Introduction to FFAG Accelerators and Storage Rings* (Beam Dynamics Newsletter, No. 43) p 19

[9] Schultz A and Pomerantz M 1963 *Secondary Electron Emission Produced by Relativistic Primary Electrons* (Phys. Rev. V. 130, No. 6)

[10] Gulbekian G, Gikal B, Kalagin I et al 2003 *Proc. 6th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC)* (Darmstadt: GSI) p 155

[11] Craddock M 2010 *Eighty Years of Cyclotrons, Proceedings of CYCLOTRONS* (Lanzhou, China) p 1

[12] Tenenbaum P and Shintake T 1999 *Measurement of Small Electron Beam Spots* (SLAC-PUB-8057. Stanford, USA)

[13] Steinhagen R 2007 *LHC BEAM Stability and Feedback Control – Orbit and Energy* (CERN-AB- 2007-049 BI. Geneva, Switzerland)

[14] Kiselev V, Muchnoi N, Meshkov O et al. 2007 *Beam Energy Spread Measurement at the VEPP- 4M Electron-Positron Collider* (Journal of Instrumentation. V. 2) p 06001

[15] Bulfone D 2008 *Overview of Fast Beam Position Feedback Systems* (Proc. of EPAC. Genoa, Italy)

[16] Bogomyagkov A, Gurko V, Zhuravlev A et al. 2007 *New fast beam profile monitor for electron- positron colliders* (Rev. Sci. Instrum. V. 78, No. 4) p 043305

[17] Scheidt K 2000 *Review of Streak Cameras for Accelerators: Features, Applications and Results* (Proc. of EPAC. Vienna, Austria)

[18] Kiselev V and Smaluk V 2004 *Measurement of local impedance by an orbit bump method* (Nucl. Instr. and Meth. V. 525, No. 3) P 433–438

[19] Naito T and Mitsuhashi T 2006 *Very small beam-size measurement by a reflective synchrotron radiation interferometer* (Phys. Rev. ST Accel. Beams. V. 9, No. 12) p 122802

[20] Elleaume P, Fortgang C, Penel C and Tarazona E 1995 *Measuring Beam Sizes and Ultra-Small Electron Emittances Using an X-ray Pinhole Camera* (J. Sync. Rad. No. 2) P 209–214

[21] Meshkov O, Gurko V, Zhuravlev A et al. 2002 *The Upgraded Optical Diagnostic of the VEPP-4M Collider* (Proc. of EPAC. Paris, France)

[22] Balakin V, Bazhan A, Lunev P et al. 1994 *Beam Position Monitor with nanometer resolution for Linear Collider* (Proc. of EPAC. London, UK)

[23] Cherepanov V 1995 *Image Current Monitor for Bunched Beam Parameters Measurements* (Proc. of DIPAC. Travemunde, Germany)

[24] Smalyuk V 2009 *Diagnostics of charged particle beams in accelerators* (Ed. Corr. RAS N.S. Dikansky. Novosibirsk: Parallel) p 294

[25] Skuratov V, Teterev Yu, Lishilin O, Zager V, Krylov A and Kalagin I 2014 *Measurement of heavy ion energy at the test facility of electronic components* (Instruments and Experimental Techniques. T. 57. N1) P 11–16.

[26] Wolf B 1995 *Handbook of ion sources* (Boca Raton, FL: CRC Press)

[27] Kisielinski M and Woitkowska J 2007 The proton beam energy measurement by a time-of-flight method *Nukleonika* **52**(1) p 3
[28] Pavlov L, Nikonova G and Shchelkanov A 2019 Development of a system of diagnostics of a cyclotron beam with the possibility of adjustment of accelerator parameters *(Proc. Int. Conf.: Information Technology and Management Automation. Omsk)* P 260–264
[29] Abbott M 2008 Performance and Future Developments of the Diamond Fast Orbit Feedback System *(Proc. of EPAC. Genoa, Italy)* p 292
[30] Yao C-Y, Norum E and Di Monte N 2007 An FPGA-Based Bunch-to-Bunch Feedback System at the Advanced Photon Source *Proc. of PAC 07* p 440
[31] Dehler M, Marinkovic G, Kramert R et al. 2007 State of the SLS Multibunch Feedback *(Proc. of APAC. Indore, India)*
[32] Nakamura T, Kobayashi K and Zhou Z 2008 Bunch by Bunch Feedback by RF Direct Sampling (Proc. of EPAC 2008. Genoa, Italy)
[33] Ritt S, Dinapoli R and Hartmann U 2004 Application of the DRS chip for fast waveform digitizing (Nuclear Instruments and Methods *Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* V **623** I 1 pp 486–488
[34] Esimhanova A and Nikonova G 2018 Virtual Device For Processing The Signals From MEMS Pressure Sensors *International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices* (Erlagol, Novosibirsk) pp 676–680
[35] Korn G and Korn T 1968 *Mathematical Handbook for Scientists and Engineers* (New York: McGraw Hill Book Company) p 571
[36] Najim K and Kehtarnavaz N 2005 *Digital Signal Processing System-Level Design Using LabVIEW* (Newnes: Elsevier) p 304

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