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FINAL REPORT ON THE START PROGRAMME

Beam parameters restoration at the NICA accelerator complex – based on fast and parametric current transformers data

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Abstract

The achievement of design parameters in complex accelerator facilities, such as NICA, represents a critically important task for successful scientific research in the field of elementary particle physics. To ensure stability and high precision operation of accelerators, meticulous tuning and optimization of system components are required. The development of mathematical models describing particle dynamics within accelerators plays a pivotal role in predicting the behavior of particle beams and identifying factors influencing their motion. The analysis of data from diagnostic equipment is equally crucial, enabling the monitoring of beam characteristics and the detection of possible anomalies. This contributes to the stable and reliable operation of accelerators and the successful realization of scientific investigations.

This work is focused on the development and enhancement of mathematical models depicting the dynamics of particle motion within accelerators, as well as the analysis of signals from diagnostic equipment to provide a deeper comprehension and optimization of NICA accelerator operation.

Contents

Introduction

Accelerator complexes play a pivotal role in contemporary research within the realms of elementary particle physics and nuclear physics. To ensure stability, precision, and the attainment of design parameters, a meticulous calibration and optimization are necessary in accelerator operation. This pertains to the imperative control of the motion of charged particle beams within the accelerator.

The objective of this endeavor is the restoration of parameters for charged particle beams within the NICA accelerator complex through the utilization of signals from fast and parametric current converters. Achieving this goal involves the formulation and refinement of mathematical models that elucidate the dynamics of particle motion within accelerators, in addition to the analysis of signals derived from diagnostic equipment.

1. Development and enhancement of mathematical models describing the dynamic motion of charged particles within the NICA accelerator. This encompasses the consideration of interactions between the beam and resonators, magnets, and other accelerator components.

2. Analysis of signals from fast and parametric current converters to restore beam parameters such as position, shape, and distribution. This process aids in monitoring the stability of particle motion and in ensuring precise accelerator calibration.

3. Optimization of NICA accelerator parameters based on the acquired diagnostic equipment data. The aim is to enhance the stability and precision of accelerator performance, thereby achieving design parameters and facilitating high efficiency in scientific research endeavors.

4. Implementation of experiments and tests on the NICA accelerator complex to verify and validate the efficacy of the developed mathematical models and signal analysis methodologies.

The cumulative outcome of this effort will foster the improvement of stability and precision in NICA accelerator operations, consequently bolstering the successful realization of scientific experiments in the domains of elementary particle physics and nuclear physics.

1. Introduction to the detector

1.1. The NICA accelerator complex

The NICA accelerator facility (Nucleotron-based Ion Collider fAcility) represents an exceptional research complex, developed collaboratively by Russian and German companies, as depicted in Figure 1. Its intricate system comprises an injector, a booster, a modernized nucleotron accelerator, and two storage collider rings, providing unparalleled opportunities for investigating the structure of nuclear matter and conducting fundamental experiments in elementary particle physics [1].

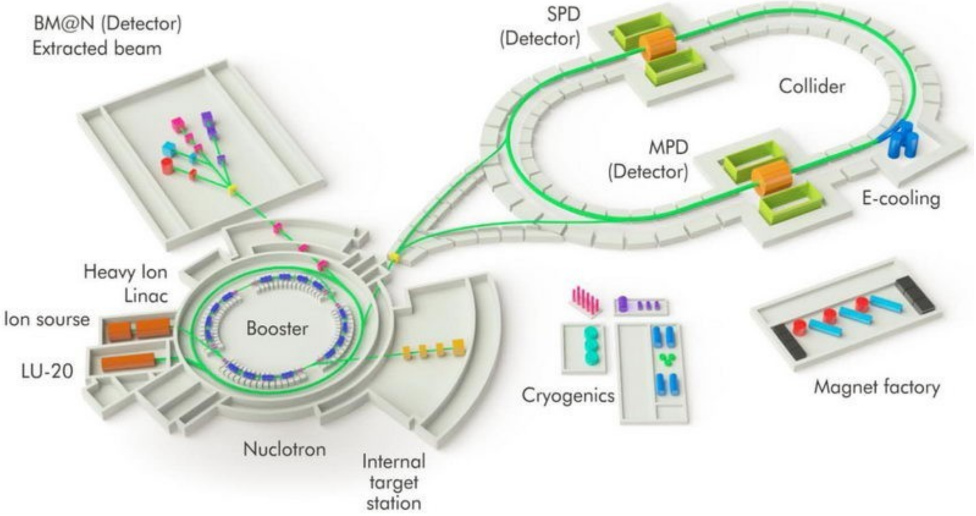

Figure 1 – NICA Layout

The injector constitutes a vital segment of the facility, facilitating the introduction of ions into the accelerator system. It encompasses a heavy ion source, a Heavy Ion Linear Accelerator (HILAC), and a pre-injector module. This stage provides initial ions which are subsequently accelerated and brought to the required energy levels in subsequent accelerators.

A pivotal component of the accelerator complex is the synchrotron accelerator housed within the existing synchrophasotron ring in Dubna. It is responsible for accelerating ions to high energies, reaching up to 600 MeV/nucleon. To achieve such elevated energies, the synchrotron incorporates intricate features such as ultra-high vacuum and electron cooling.

The modernized nucleotron provides beams of protons, deuterons, and heavy ions at various energy levels. It can reach a maximum energy per nucleon of 5.8 GeV for certain nuclei and 4.5 GeV for Au-197 nuclei. The initial luminosity of the accelerator is set at $10^{24} cm^{-2} s^{-1}$ and has the potential for rapid increase up to $10^{25} cm^{-2} s^{-1}$. The overall designed power of the facility amounts to $10^{27} cm^{-2} s^{-1}$, encompassing features such as an electron cooling system and radiofrequency resonators.

In the initial stages of the accelerator's operation, symmetrical collisions of heavy ions such as Au-178, Pb-208, and Bi-209 will be conducted. The collision energy will vary from 7 to 9.46 GeV, with a preferred collision energy of 9.2 GeV for comparative analysis with experiments at RHIC-STAR.

However, the most intriguing prospect for NICA lies in the potential to facilitate Au + Au collisions with collision energies of up to 11 GeV in the long term. Additionally, NICA enables the creation of beams of polarized protons and deuterons with a center-of-mass energy of up to 27 GeV and a luminosity of $10^{32} cm^{-2} s^{-1}$. The collider rings, operating on superconducting magnets with a dual aperture, provide a maximum dipole magnet field of 18 T. Systems of electronic and stochastic cooling are implemented to sustain luminosity within the collider, thereby enhancing its productivity and efficiency.

The NICA accelerator complex opens up broad opportunities for the investigation of nuclear matter and elementary particles' structure, rendering it a significant tool in contemporary physics research.

1.2. Device and operating principle of the fast and parametric transformers

The diagnostics of charged particle beam characteristics in accelerators play a pivotal role in ensuring stability and achieving the desired parameters of the accelerated beam. Broadly, the dynamics of charged particle motion in accelerators can be divided into transverse (dominated by the influence of magnetic elements) and longitudinal (associated with synchrotron motion) components, which are reflected in diagnostic methods and tools. For the study of synchrotron motion, including fast current transformers and parametric current transformers are employed [5].

The fast current transformer, as shown in Figure 2, enables the measurement of the variation in current passing through a beam of charged particles with high temporal resolution. A distinct feature of the fast current transformer is its capability to operate only with bunched beams, which allows it to be utilized for investigating synchrotron motion, particularly in reconstructing the particle momentum distribution from deviation.

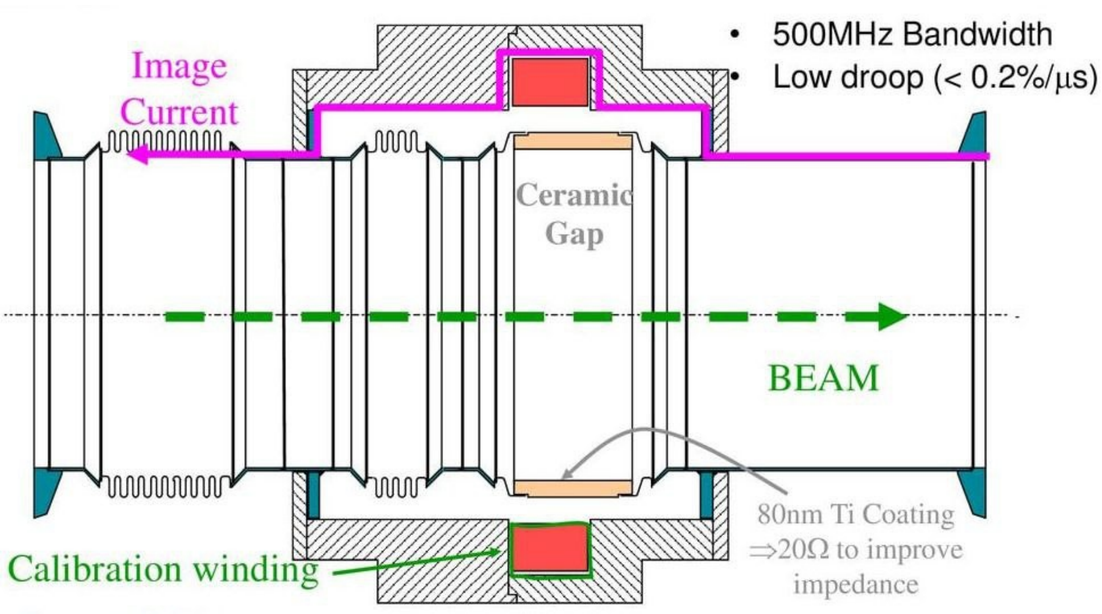

Figure 2 – Fact Current Transformer layout

A fundamental distinction of the parametric current transformer (PCT) lies in its capability to operate with an unbunched beam, as depicted in Figure 3. Its operation is based on the modulation of the magnetic field contingent upon particle displacements within the beam. Alterations in the magnetic field induce a varying current, which is proportionate to the change in particle momentum. This method also ensures high accuracy and temporal resolution in measuring synchrotron motion parameters.

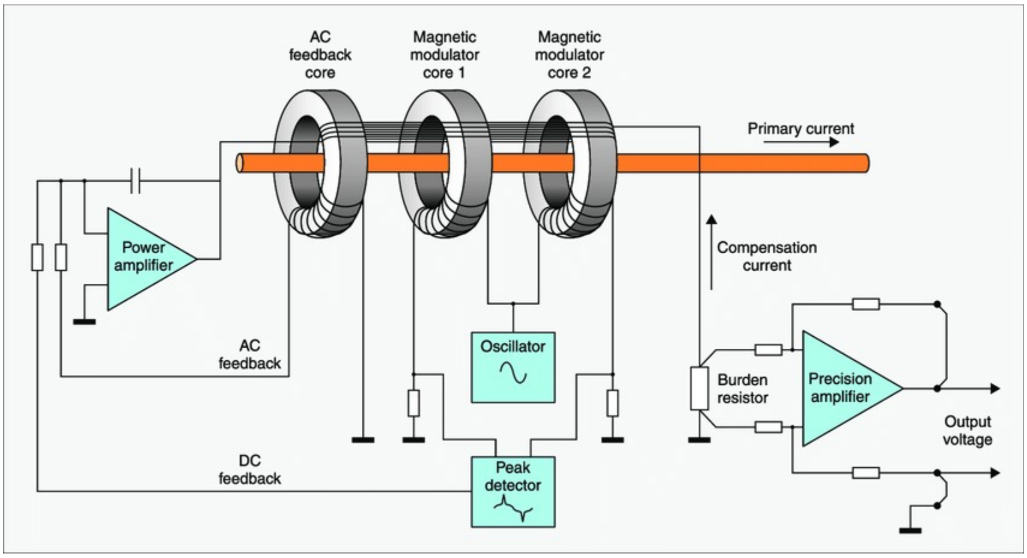

Figure 3 – Parametric Current Transformer

Investigating the dynamics of synchrotron motion through the utilization of fast and parametric current transformers is a pivotal task in the diagnostics of charged particle beams in accelerators. This approach enables researchers to acquire crucial information necessary for the tuning and optimization of accelerator operations. It ensures a high level of beam stability and quality, ultimately contributing to the successful execution of scientific research and experiments in the fields of elementary particle physics and nuclear physics [2].

1.2.1. Interpretation of the signal using the fast and parametric transformers

Both types of current transformers are employed to measure changes in the momentum of particles within a beam, but they operate based on different principles.

1. Fast Current Transformer:

- In the fast current transformer, measurements are conducted by detecting changes in the current passing through a sample (with a ferrite ring) over time.
- The signal obtained from the fast current transformer presents a temporal profile of current variation, reflecting changes in particle momentum within the beam over time.
- Interpreting this signal allows researchers to determine beam motion dynamics, such as its energy characteristics, beam length, and structure. Such data can be utilized for accelerator control and optimization, aiming for high beam stability and precision.

2. Parametric Current Transformer:

- In the parametric current transformer, changes in the magnetic field are generated based on particle displacements within the beam. These changes in the magnetic field induce a varying current in the transformer.
- The signal from the parametric current transformer also provides information about beam motion dynamics, specifically, the change in its momentum over time.
- Through signal analysis and interpretation, researchers can obtain precise data about synchrotron motion parameters, such as momentum, particle distribution, and beam shape.

Both types of current transformers provide information about particle motion dynamics within a beam with high temporal resolution. This is a crucial aspect of the diagnostics of charged particle beams in accelerators.

2. Dynamics of motion of charged particles

The dynamics of charged particle motion in accelerators is determined by a set of crucial physical parameters, which can be measured or reconstructed using various methods. Some of the fundamental formulas and parameters associated with motion dynamics include the phase space volume, transverse motion frequencies, betatron functions, resonances, synchrotron motion, and more.

2.1. Phase volume

In the context of particle accelerators, the phase space represents a multi-dimensional space where each measurable physical quantity associated with particles (such as coordinates and momenta) constitutes one of the coordinates within this space. For a system of N particles in three-dimensional space, the phase space would be 2N-dimensional [4]. The formula for calculating the phase space volume is as follows:

$$V=\sigma_x\cdot\sigma_y\cdot\sigma_{p_x}\cdot\sigma_{p_y}, \qquad (1)$$

where σ_x – represents the standard deviation of the horizontal position, σ_y – represents the standard deviation of the vertical position, σ_{p_x} – represents the standard deviation of the horizontal momentum, σ_{p_y} - represents the standard deviation of the vertical momentum.

The phase space volume describes the position and motion of particles within the accelerator. It plays a crucial role in the analysis and design of accelerators as it helps understand how particles will stably move within the accelerator, how they will interact with focusing systems, and how they will interact with each other.

The phase space volume can also be used to study the stability of particle beams. Changes in the shape or size of the phase space volume can indicate various anomalies or nonlinearities in the accelerator's operation that might affect the beam's structure and characteristics.

2.2. Betatronic frequencies

When a particle moves within the magnetic structure of an accelerator, deviations in transverse coordinate or momentum from the equilibrium orbit lead to the emergence of betatron oscillations. The linear betatron oscillations of a particle in a cyclic accelerator are described by Hill's equation in the co-moving coordinate system [2].

$$x''+K_x(z)x=0, y''+K_y(z)y=0, \qquad (2)$$

where $x' = \frac{dx}{dz}, y' = \frac{dy}{dz}, K_x(z) = \frac{1}{B\rho}\frac{\partial B_y}{\partial x} + \frac{1}{\rho^2}, K_y(z) = \frac{1}{B\rho}\frac{\partial B_y}{\partial x} + \frac{1}{\rho^2}$, B – magnetic field, ρ – radius of curvature of the trajectory. Here x represents horisontal plane , y – vertical.

The solution, for instance, in the vertical plane, appears as follows: two independent solutions [4].

$$y_1(z) = e^{\frac{i\mu z}{L}} p_1(z), y_2(z) = e^{\frac{-i\mu z}{L}} p_2(z),$$

where μ is the characteristic coefficient of the differential equation, which is determined by the following relationship:

$$cos\mu = \frac{1}{2} traceM(s)$$

$p_1(z)$ and $p_2(z)$ are periodical functions[4]:

$$p_i(z+L) = p_i(z), i = 1,2,$$

where L – length of the magnetic action period.

The temporal variation of the transverse coordinate and momentum is periodic but not sinusoidal. As a result, the oscillation spectrum will be complex, containing harmonics of the betatron frequency.

In a cyclic accelerator, the horizontal Q_x or vertical Q_y betatron frequency is defined as the number of betatron oscillation periods that fit within one revolution:

$$Q = \frac{\varphi(z+C) - \varphi(z)}{2\pi} = \frac{1}{2\pi}\int_{z}^{z+C}\frac{dz}{\beta(z)}, \tag{3}$$

where φ is the horizontal or vertical betatron phase advance, β is the corresponding beta function, and C is the accelerator perimeter [2].

Betatron frequencies are crucial parameters of an accelerator, greatly influencing its efficient operation. The stability of beam motion, luminosity in colliders, and the brilliance of synchrotron radiation sources are largely determined by the position of the working point of the betatron frequencies on the plane of betatron resonances. That's why practically all accelerator setups employ systems for measuring betatron frequencies.

The integer part of the betatron frequency can be readily determined by the number of periods of the wave-like orbit distortion caused by a local perturbation of the magnetic field.

The fractional part of the betatron frequency can be measured through spectral analysis of an array of coherent betatron oscillation samples, recorded by a beam position monitor during each revolution.

2.3. Resonance

In particle accelerators, resonant phenomena occur when the oscillation frequencies of particles match the characteristic frequencies of the acceleration system. Resonance can lead to unwanted effects and instability in beam motion, negatively impacting the accelerator's performance and the quality of scientific research.

To better understand resonant phenomena in accelerators, let's consider the formula for calculating the synchronous frequency ω_s. This frequency corresponds to the rate at which the beam moves synchronously with the variable electric field within the accelerator. The synchronous frequency can be determined using the formula:

$$\omega_s = \frac{q}{m} \cdot B_0, \tag{3}$$

where q is the charge of the particle, m is the particle's mass, and B_0 is the magnetic induction in the main magnetic field of the accelerator.

When the frequency of particle oscillations coincides with the synchronous frequency, a resonance condition occurs, which can lead to the instability of beam motion. To prevent or mitigate undesirable resonance effects, accelerators employ methods of control and correction, such as adjusting magnetic fields or using resonators.

Control of resonance conditions and stabilization of beam motion are crucial aspects of charged particle beam diagnostics in accelerators. Measuring beam parameters and monitoring its motion allow for the timely detection of resonance phenomena and the implementation of necessary measures to ensure the stability and reliability of accelerator operation during experiments.

2.4. Synchrotron motion

Synchrotron motion $\frac{dp}{p}$ refers to the dynamics of charged particles in an accelerator that is associated with the change in their momentum p relative to the momentum they initially received from the accelerator. This effect arises due to the non-uniformity of the magnetic field in the accelerator, leading to various cyclic variations in particle velocity.

For a more detailed description of synchrotron motion, let's consider the formula that describes the change in particle momentum dp as a function of its momentum p and the magnetic field B of the accelerator:

$$\frac{dp}{p} = q \cdot B \cdot ds, \tag{4}$$

where q is the charge of the particle, B is the magnetic induction in the accelerator's magnetic field, and ds is the length of the trajectory element of the particle traversed in the magnetic field.

From this formula, it can be seen that the change in particle momentum is proportional to its momentum p, the magnetic induction B, and the length of the trajectory element ds. Synchrotron motion is precisely determined by this relationship and is the result of particles interacting with an inhomogeneous magnetic field.

Synchrotron motion is important for diagnosing charged particle beams in accelerators as it can lead to beam smearing and deterioration of their quality.

3. The practical part

This work provides a detailed description of the algorithm for accelerator data analysis based on time series. It discusses the methodology and develops the code for processing experimental data, along with describing the input parameters and computations involved.

3.1. Data

Two data files were used for analysis: one containing information from the fast current transformer and another containing data from the RF station's signal generator. Both files consist of time series data obtained during the operation of the accelerator.

Additionally, predetermined parameters included the accelerator's revolution period, a time interval that determines the data sampling rate, as well as numerical values corresponding to the signal shift from the signal generator and the end shift, respectively. These values are used for time correction or for locating specific time intervals of interest.

3.2. Filtering algorithms

In this study, three crucial signal processing algorithms are employed, exerting a significant influence on the accuracy and reliability of the analysis. Each of these algorithms plays an essential role in obtaining meaningful parameters of charged particle beams within the NICA accelerator complex.

The first algorithm, Zero Crossing, enables the determination of time intervals between the crossings of the RF signal generator waveform and the calculation of phase-related values associated with them. This algorithm contributes to the identification of significant temporal points of zero crossings. A vital aspect of this process involves phase discretization of the RF signal generator, allowing for a more precise determination of phase offset from the initially selected value. The algorithm's essence is as follows. Within each interval, the signal is approximated by a function of the form:

$$A\cos x + B\sin x + C$$

The coefficients are determined using the method of least squares. Subsequently, based on these coefficients, the amplitude and phase are calculated. The next algorithm aims to correct phase values based on the minimal values in the signal. This algorithm takes into account the differences between signals measured in different time intervals and compensates for these differences to refine phase values. Such correction significantly enhances the precision of computations and the interpretation of results.

Another significant algorithm employed for sensor signal processing is the smoothing method with averaging. The choice of this method for sensor signal processing was made due to the following reasons:

1. Noise elimination;
2. Variability smoothing;
3. Accuracy improvement.

The effective application of these algorithms allows for the extraction of the required characteristics of charged particle beams and can be applied across all setups within the NICA accelerator complex. Their interaction ensures the reliability and accuracy of the obtained results, contributing to a deeper analysis of particle behavior within the accelerator and additionally confirming the significance of this research.

3.3. Restoring the real parameters

For a detailed analysis of synchrotron motion under the influence of a high-frequency (HF) accelerating station, data collection was performed at a high sampling frequency using a Fast Current Transformer (FCT) and the HF generator of the accelerating station.

The collected data were time-aligned to correspond to the accelerator's period. This time interval was determined, taking into account the time delay until the beam's injection into the facility.

The visualization of the results is presented in Figure 4. This graph displays two sets of data: the first one is associated with measurements from the FCT, and the second one corresponds to data from the RF generator. To enhance the clarity of temporal intervals, different colors and line styles were utilized.

The horizontal axis of the graph reflects the duration of the charge injection period, while the vertical axis represents signal amplitudes. The vertical axis range was limited to emphasize details and ensure data clarity.

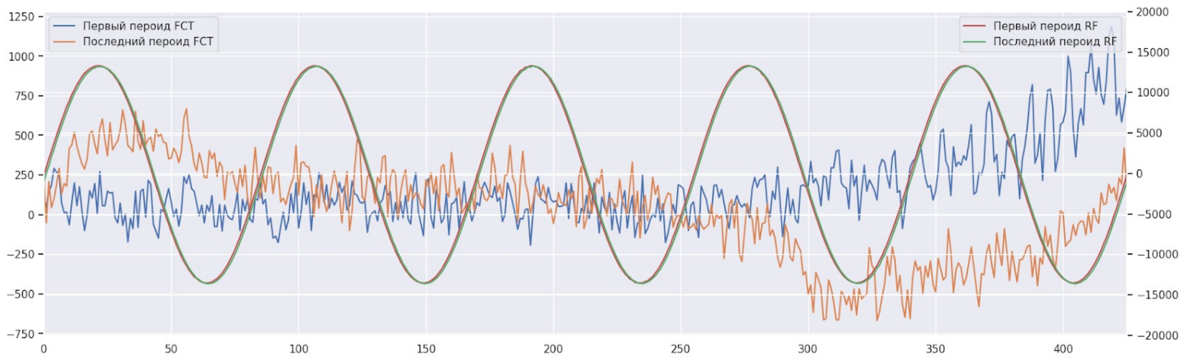

Figure 4 — Signals from Two Sensors

The presented graphical representation not only allows for a more visual analysis of signal dynamics over time but also reveals the correlation between measurements related to beam injection into the accelerator.

Further analysis was conducted on the behavior of the period time duration, and the results are presented in Figure 5.

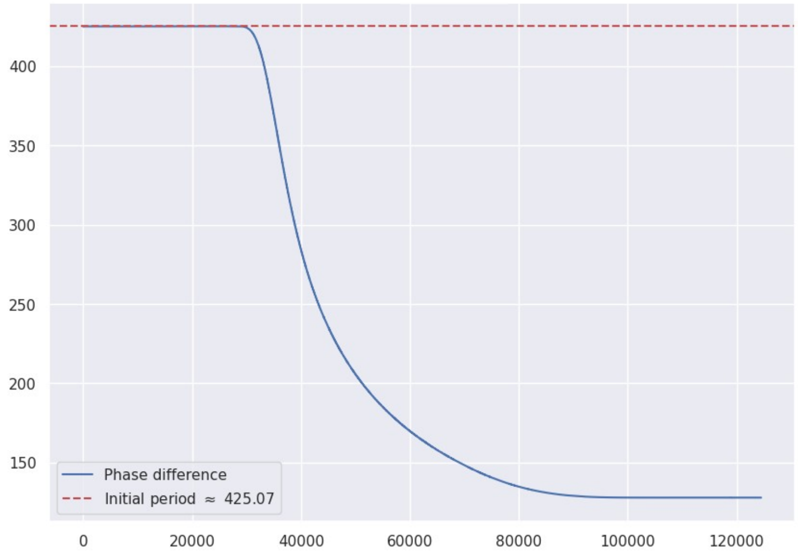

Figure 5 – Period Time Duration

This graph depicts the relationship between phase changes and time during the initial stage of acceleration. Each point on the graph represents the phase change between adjacent moments in time. To enhance understanding of the results, a horizontal dashed line indicating the initial period value has been introduced on the graph. This line is highlighted with a red dashed line to better track the initial value.

Analysis of this graph allows for a visual examination of phase changes over time. It provides information on how the signal phase evolves and fluctuates throughout the studied period. Additionally, a graph illustrating normalized signal amplitudes has been constructed, as shown in Figure 6.

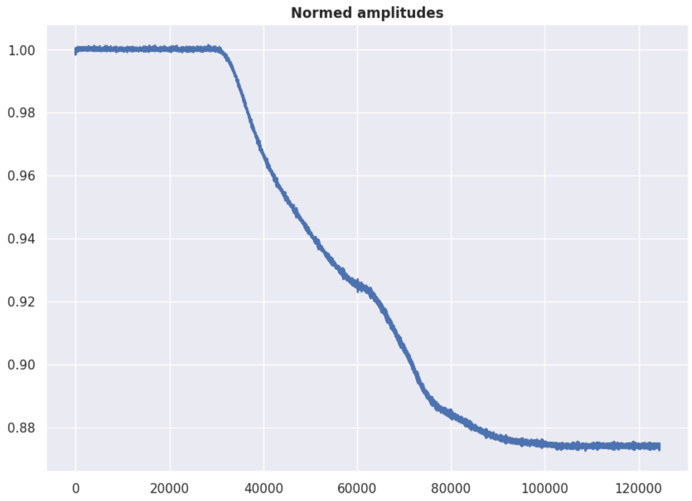

Figure 6 – Normalized Signal Amplitudes заглавие на графике

For amplitude normalization, each value was divided by the initial amplitude value (first data point). This allows establishing the relative change in signal amplitude compared to its initial value.

It's worth emphasizing that this graph illustrates the dynamics of signal amplitude changes over time. It also reveals potential oscillations and modulations within the specified time interval. Such visual representation enables a deeper understanding of the dynamics of signal amplitude changes during the studied period.

A key parameter of accelerator performance is the intensity of the accelerated beam. To analyze losses during the acceleration process, a dependency illustrating the change in beam intensity has been constructed, as shown in Figure 7.

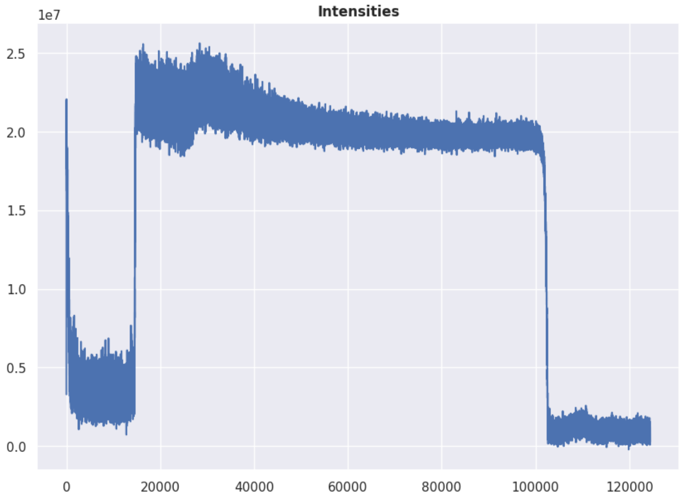

Figure 7 – Intensity Variation

It can identify peak intensity values and also reveal fluctuations and variations in intensity within the considered time period. Since the beam intensity in the accelerator cannot naturally increase (except for the accumulation process), the graph allows for a deeper analysis to uncover key processes directly related to signal collection and transformation.

In addition, for signal change analysis, the averaged minimums of the signal from the Fast Current Transformer (FCT) were calculated and depicted, as shown in Figure 8.

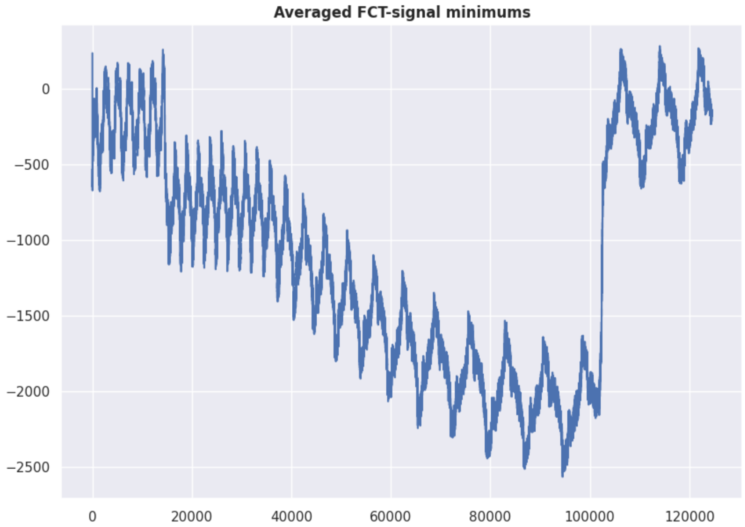

Figure 8 – Averaged Minima

The approach of averaging minimum signal values allows identifying general trends or changes in signal characteristics as it smoothes out possible fluctuations and highlights the main features of the signal. The application of this method helps to more clearly discern key signal traits.

Applying the described methodology to analyze the signal from the second stage of acceleration allows constructing a graph depicting the beam intensity variation throughout the acceleration process and enables comparisons between cycles, as shown in Figure 9.

The graph includes two curves, each representing a specific signal. Each curve is divided into two parts – the "first half" and the "second half," representing different time segments.

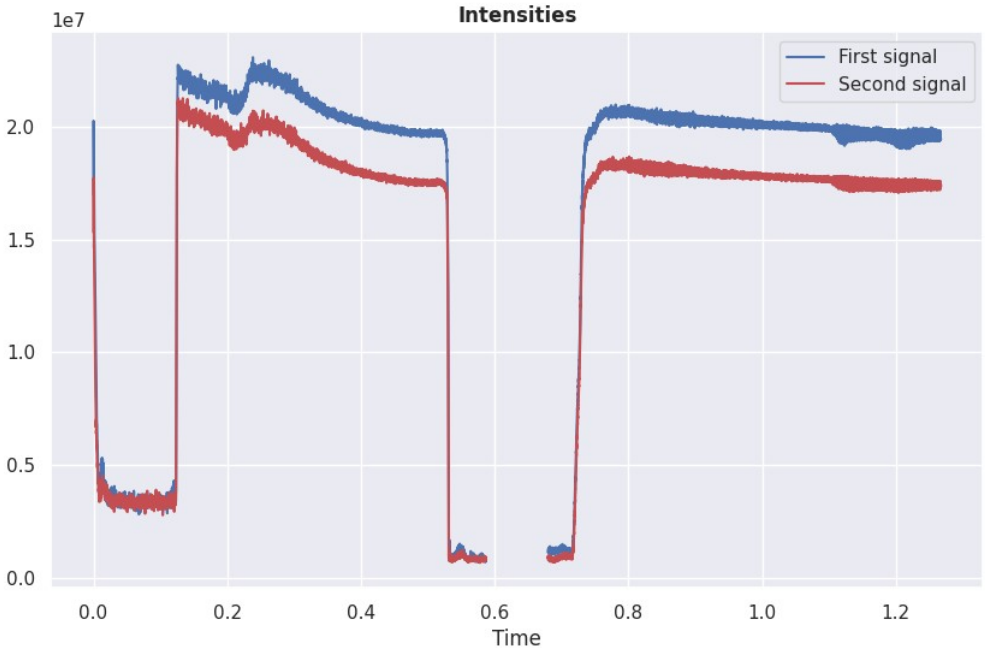

Figure 9 – Behavior of Signals for Two Different Initial and Final Time Intervals

This graph allows for the comparison of intensities between two different signals at various time points. It vividly demonstrates how signal intensities change over the observed period and which characteristic features are present in different time phases. Such representation enhances the understanding of dynamics and the relationship between signals in different parts of the investigated period.

Next, calculations of Lorentz factors were performed, characterizing particle behavior. The results of this analysis are presented in Figure 10, illustrating the dynamics of beta Lorentz factors' change for two different signals at different time periods.

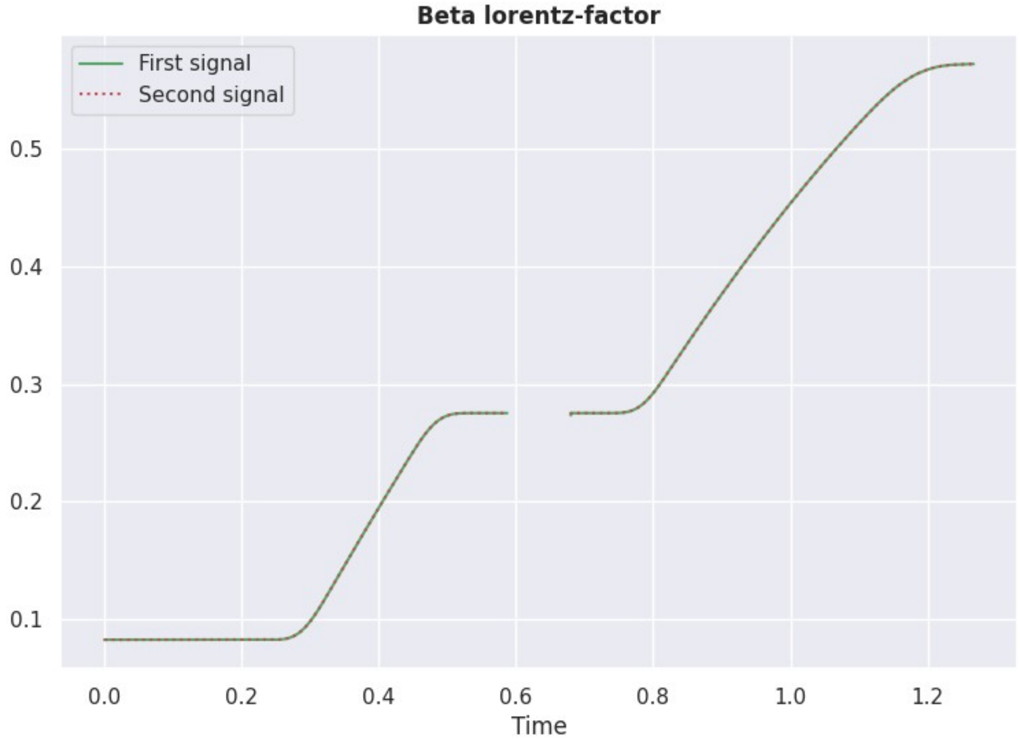

Figure 10 – Variation of Beta Lorentz Factor for Two Time Intervals

The graph contains four curves, each corresponding to a specific signal and its "first half" and "second half". This graph allows analyzing how the beta Lorentz factor changes over time for different signals. It provides insight into the dynamics of particle velocity changes during their acceleration. Continuing the analysis, additional graphs are presented in Figures 11-13:

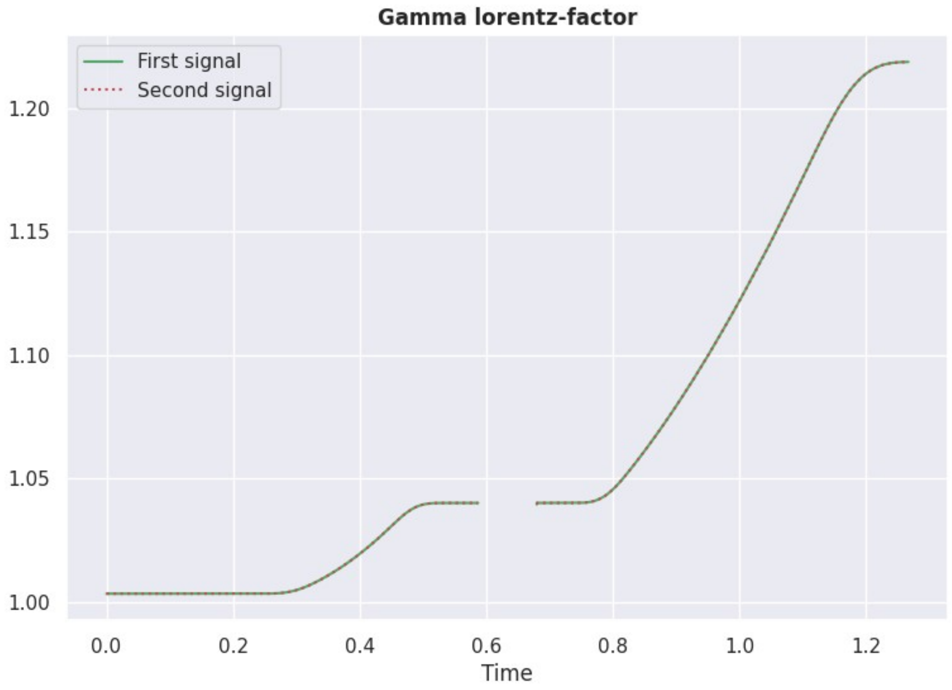

Figure 11 – Variation of Gamma Lorentz Factor for Two Time Intervals

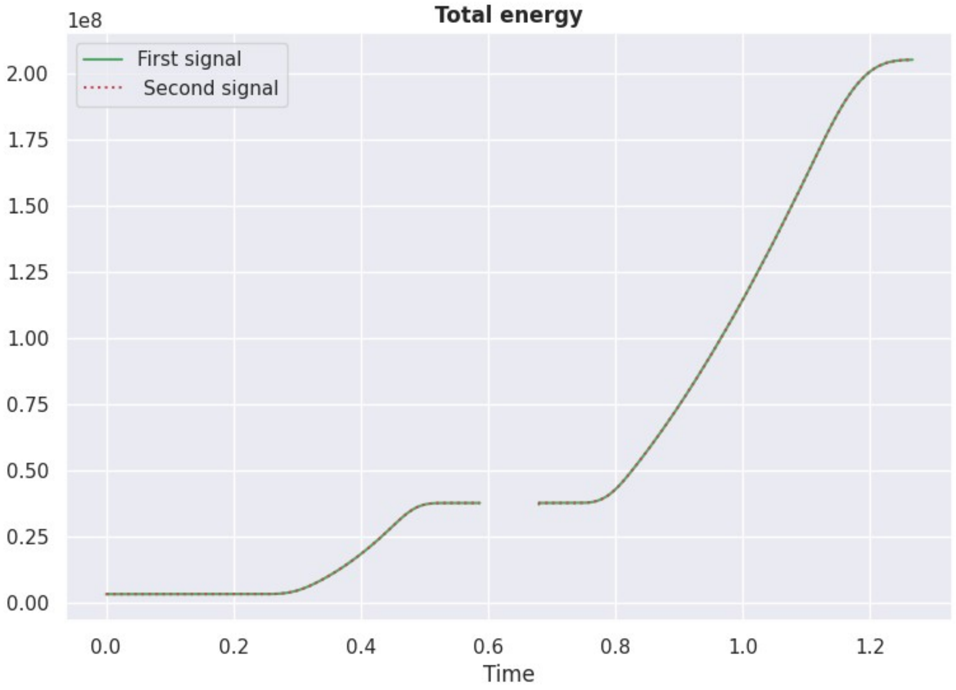

Figure 12 – Variation of Total Energy for Two Time Intervals

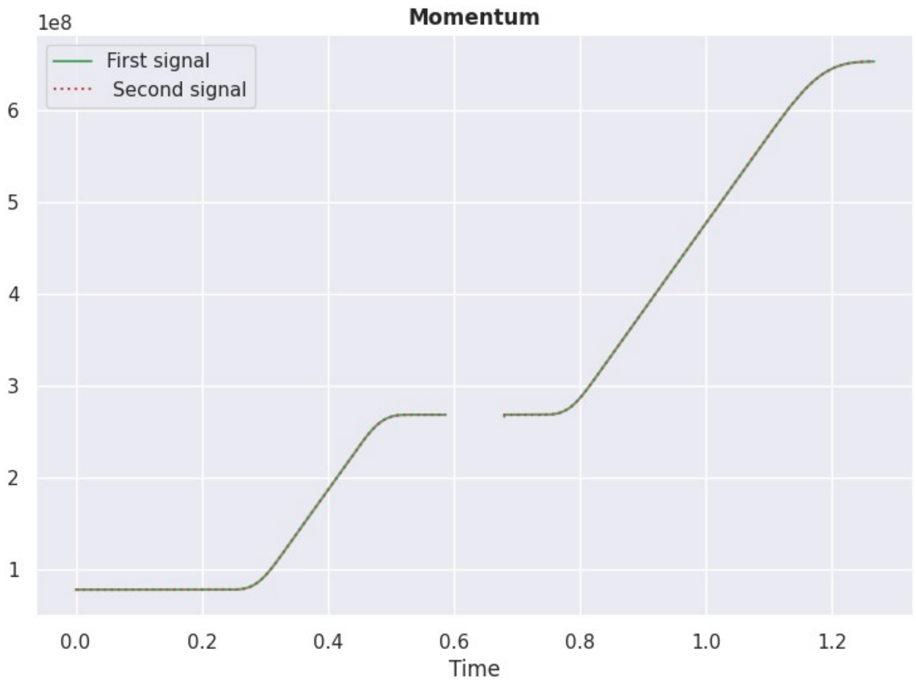

Figure 13 – Variation of Momentum for Two Time Intervals

These graphs provide a more detailed insight into the dynamics of changes in the gamma Lorentz factor, total energy, and particle momentum at different moments in time. Exploring these characteristics helps to better understand the impact of acceleration on particle parameters and their temporal motion.

Furthermore, an analysis of the intensity changes of signals from fast and parametric converters over time was conducted. This analysis also included a smoothed signal from the magnetic field sensor. The visualization of this analysis is presented in Figure 14.

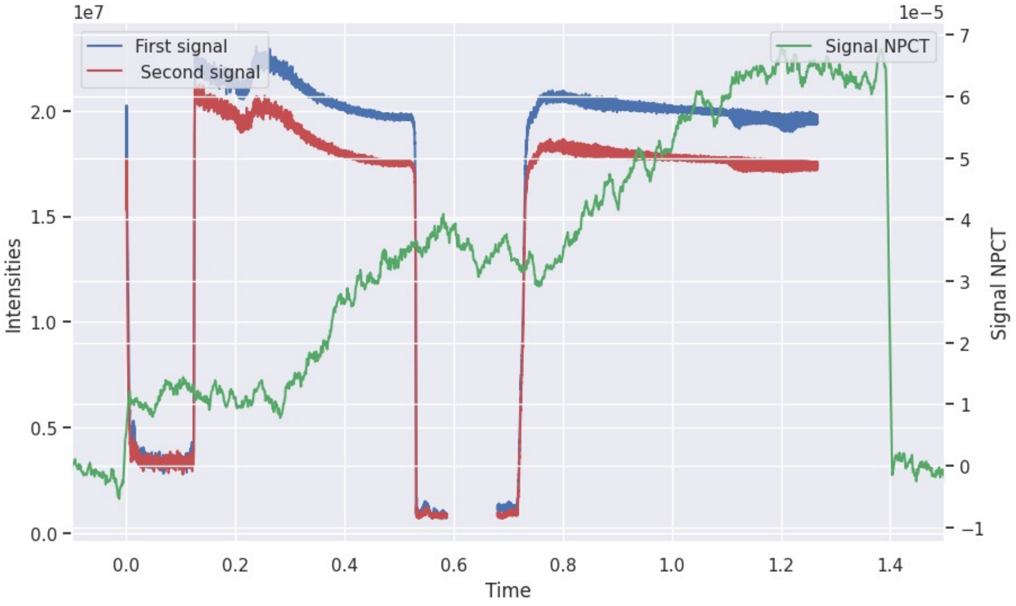

Figure 14 – Comparison of Signal Intensity Behavior with Smoothed Magnetic Field Sensor Signal.

To ensure a more accurate comparison, a second scale was added to the graph to display the smoothed signal from the magnetic field sensor. This allows for a clearer assessment of the correlation between the signal intensities from the converters and the smoothed sensor signal.

This graph provides information about how the signal intensities change over time and how these changes may be related to the behavior of the smoothed magnetic field sensor signal. This observation is of significant importance for the analysis and optimization of the processes of accelerating charged particles in the accelerator complex. Analyzing the correlation between the signals and the smoothed sensor signal can help more precisely determine the relationships and the influence of acceleration parameters on signal intensities.

This work also included a detailed analysis of the dependence of the change in the total revolution time within the Booster. The graphical representation of this dependence is presented in Figure 15.

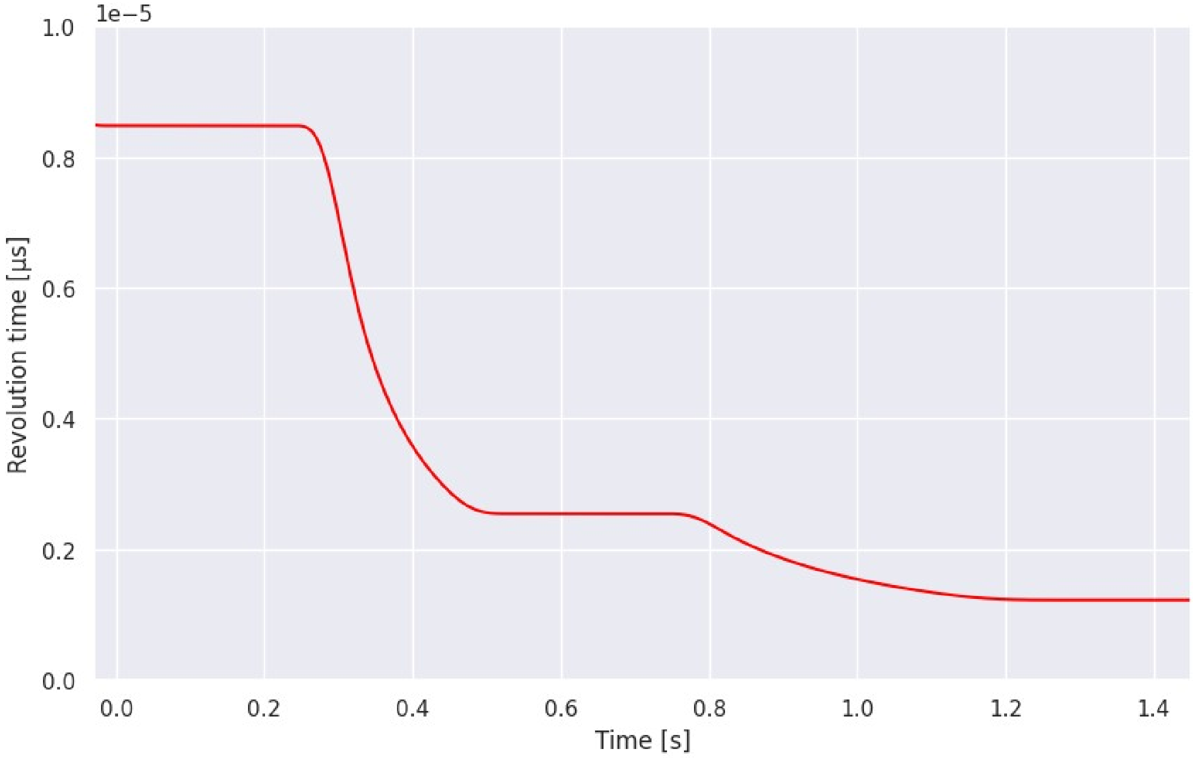

Figure 15 – Change in Revolution Period of the Beam

This graph contains data points, each representing a specific time moment. For each data point, the corresponding value of the beam revolution period of charged particles was calculated. The calculation of this period is based on various parameters, such as the magnetic field, particle charge, mass number, speed of light, and other characteristics.

This analysis allows for a deeper understanding of how the beam revolution time changes within the accelerator complex over time.

One of the useful graphs for analysis is the following, which illustrates the dynamics of the beam intensity of charged particles within the accelerator complex over time, shown in Figure 16. The graph visualizes the results of two different methods for measuring beam intensity: Fast Current Transformers (FCT) and Direct Current Current Transformers (DCCT). This analysis also includes the smoothed signal from the Non-Parametric Current Transformer (NPCT).

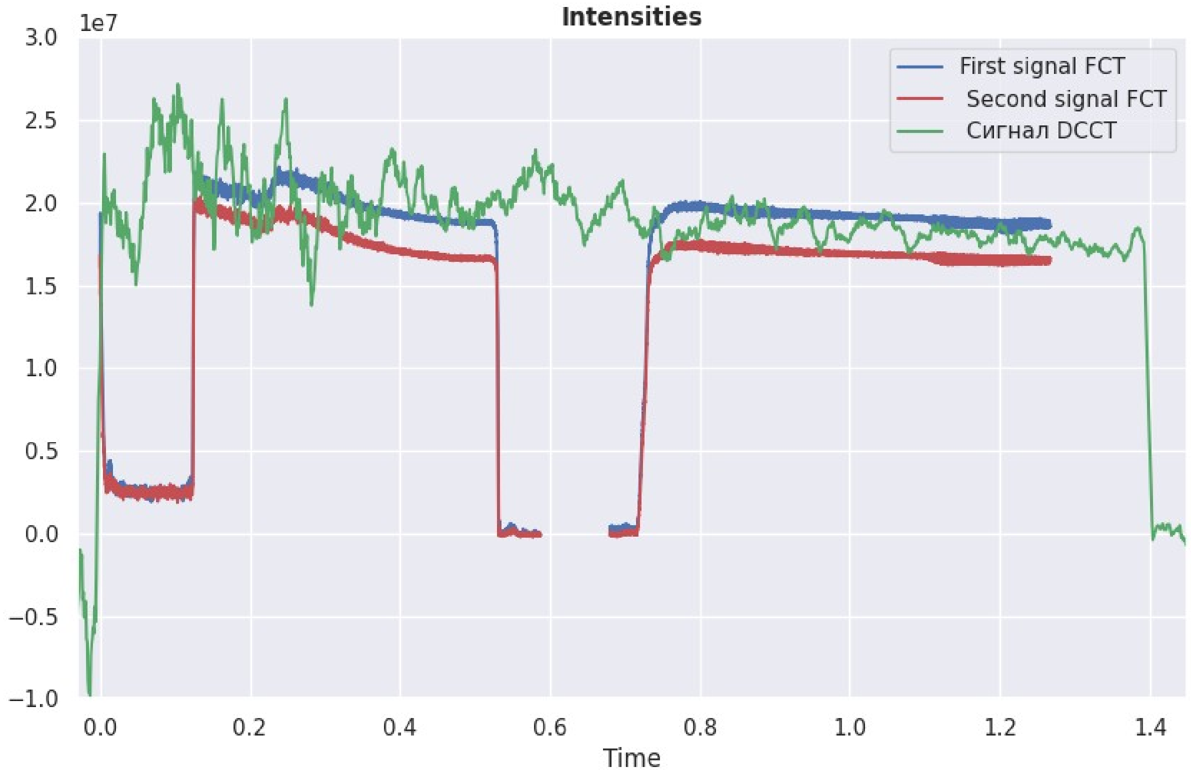

Figure 14 – Beam Intensity Variation for Two Time Moments Using Two Different Methods

The graph displays four curves representing the beam intensities for two different FCT signals (first and second signals) and the DCCT signal. It's important to note that an offset was applied to the FCT intensity values for better visibility on the graph.

To ensure a more accurate comparison, a second scale was added to the graph to display the smoothed signal from the NPCT sensor. This provides a clearer view of the correlation between the intensity signals from the converters and the smoothed NPCT signal.

This graph provides insights into how the intensity signals change over time and how these changes might be related to the behavior of the smoothed NPCT signal. This observation is crucial for analyzing and optimizing the processes of accelerating charged particles within the accelerator complex. Analyzing the correlation between the signals and the smoothed NPCT signal can help more accurately determine the relationships and the influence of acceleration parameters on signal intensities.

Conclusion

As a result of this work, the parameters of the beam of charged particles in the NICA accelerator complex have been successfully reconstructed, ensuring stability and high precision of its operation. This achievement is a crucial factor for the successful realization of scientific research in the field of elementary particle physics and nuclear physics.

To achieve this goal, mathematical models of particle dynamics in accelerators were developed and refined, along with the analysis of signals obtained from beam position monitors. This analysis enabled the control of particle shape, size, and distribution within the beam, providing vital information for scientists and researchers.

For more accurate and reliable data acquisition regarding beam parameters and its motion, highly effective signal processing algorithms were applied. This contributed to improving data quality and ensured the precision of beam parameter reconstruction.

Overall, this work has made a significant contribution to optimizing the operation of the NICA accelerator complex and enhancing its performance. The obtained results will be valuable for further research and experiments conducted on this accelerator, furthering progress in the field of elementary particle physics and nuclear physics.

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