Automated Calibration System for Beam Current Monitors

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Beam Current Monitors (BCM) measure the instantaneous current in a beam. Traditional calibration methods require an interruption of beam operation, which impacts operational efficiency. This work presents the development of an automated calibration system for BCMs to address the need for calibration without interruption of beam operation. By utilizing the pulsed nature of synchrotrons, we endeavor to create a synchronous calibration method integrated into the master timeline capable of running calibration pulses during inter-pulse gaps. Our system utilizes a Keithley 6221 current source and a Keithley 2182A nanovoltmeter controlled by custom Python-based software. We demonstrate the capabilities of successful implementation, with test calibration sweeps completed in as little as 30 ms. This improved approach should improve operational efficiency, ensure safe operation, and help mitigate beam loss, all by enabling intermittent calibration during the operation of the accelerator. The potential of this system for simultaneous calibration of multiple BCMs and integration into normal operation paves the way for improved accelerator performance and diagnostics.

I. INTRODUCTION

Beam Current Monitors (BCMs) are essential diagnostic instruments in particle accelerators. They provide data that accurately reflect the current flowing through a beamline. These measurements are critical for many applications in the operation of an accelerator. The types of BCMs we will attempt to calibrate are the Direct Current Current Transformer (DCCT) and Alternating Current Current Transformer (ACCT). Both of these current transformers are useful in different scenarios. The DCCT is used in recycler rings and synchrotrons and is particularly useful in measuring bunched or unbunched beams' DC (0Hz) components. Alternating Current Current Transformers (ACCT) BCMs are based on classical transformers, and their signal output provides accurate representations of beam current pulses over ranges of frequencies, pulse lengths, and amplitudes[1].

BCMs need to be calibrated periodically to ensure measurement accuracy. At the time of writing, calibration of BCMs at Fermilab is done during beam downtime. Usually, these opportunities appear when the accelerator is shut down for maintenance. Waiting for interruptions in beam operation to calibrate the BCMs is an inefficient and non-preventative method of operation. This current method is analogous to treating a disease after it has taken hold rather than preventing it altogether by periodically taking preventative measures. Interruptions in the beam are particularly problematic in high-energy physics experiments because beam loss can have drastic consequences, and experiments and other applications require stable, continuous beam operation.

To illustrate our goals' logistic complications and feasibility, we'll present the Muon g-2 experiment at Fermilab and its timing structure 1. This timing diagram clearly shows that the timing cycle is based on the Linac's 66.7 ms cycle time. The Linac sends a 32 μs beam pulse every 66.7 ms, leaving a 66.63 ms gap in which we will attempt calibration test pulses.

The main objective of this work is to develop an automated calibration system for BCMs that can operate during normal beam operation. Specifically, our goals include creating a synchronous calibration method that can be integrated into the master timeline of the particle accelerator. A critical functionality that we must accomplish is utilizing the inter-pulse gaps to run calibration pulses to not interfere with the operating beam. To achieve this, a Python-based program must be developed to control the calibration instruments so they can precisely run calibration pulses without affecting the beam. Implementing pulsed IV sweep and DC linear staircase sweep functionality enables the calibration of both ACCT and DCCT BCMs. We aim to achieve rapid calibration tests within the timing constraints of the available gap.

We seek to enhance the operational efficiency of particle accelerators, ensure accurate beam current measurements, and contribute to the overall safety and performance of accelerator operation by completing these objectives.

II. METHODS

Our automated calibration system for Beam Current Monitors (BCMs) combines precision hardware with custom software to achieve interpulse calibration, enabling calibration during regular accelerator operation. The methodology has three main components: hardware setup, software development, and calibration processes.

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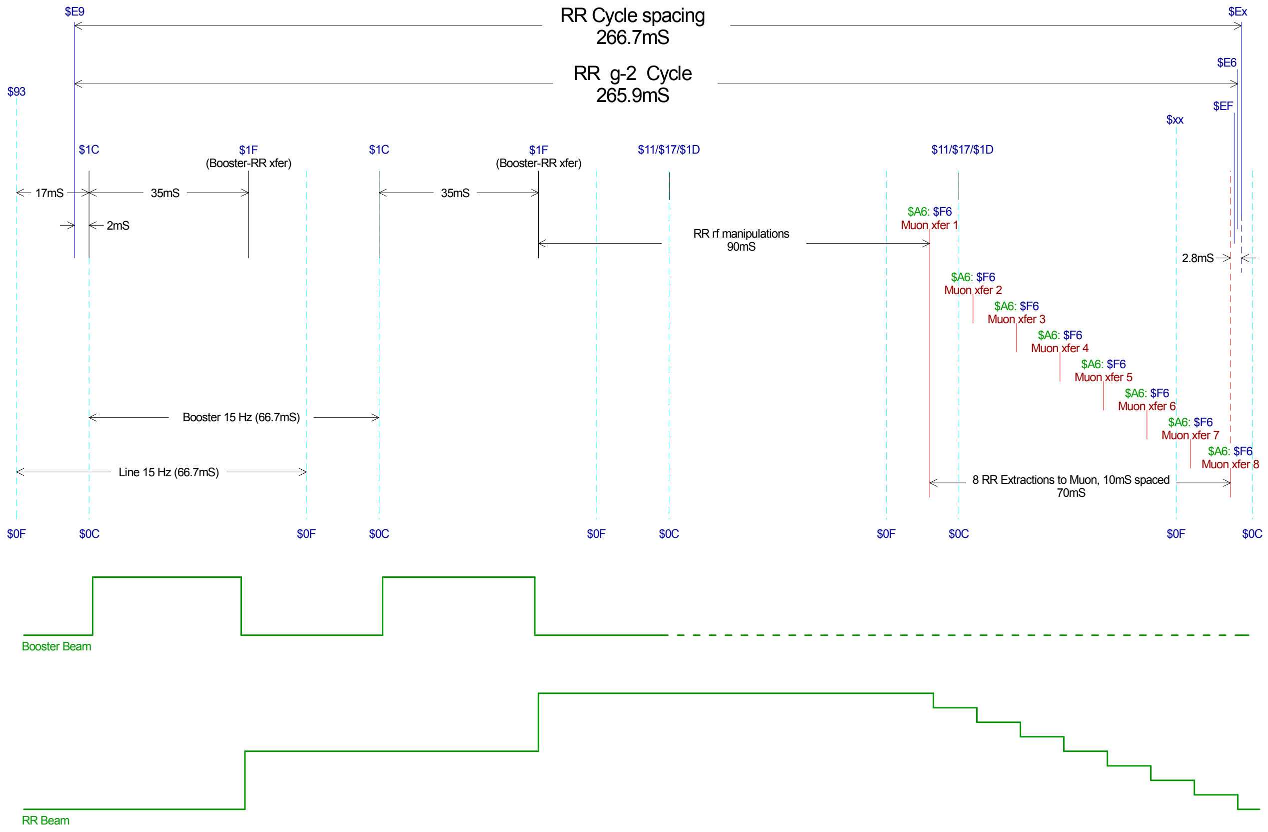


FIG. 1. This is a timing diagram of the Muon g-2 experiment, showing the 66.7 ms cycle time of the Linac.

A. Hardware Setup

The core of our calibration system consists of two primary instruments. The Keithley 6221 AC/DC Current Source generates accurate and precise calibration pulses[2]. The Keithley 2182A nanovoltmeter is used to measure the BCM response with high accuracy[3]. These instruments were chosen for their high precision, low noise characteristics, and ability to generate and measure rapid current pulses in various current sweep configurations. Figure 2 illustrates the hardware configuration.

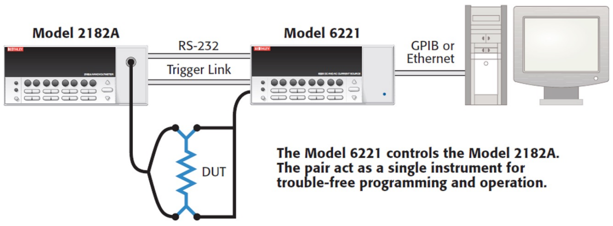


FIG. 2. Instrument setup diagram showing the connection between the Keithley 6221, Keithley 2182A, a controlling computer, and the device under test (DUT)[4].

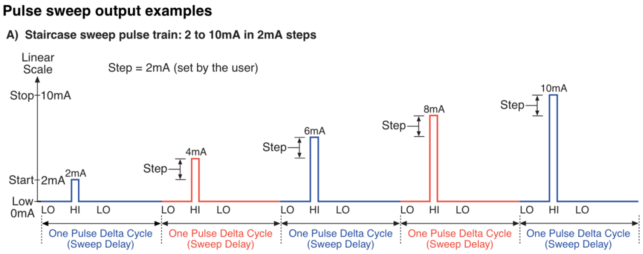


FIG. 3. This picture represents a linear sweep pulse delta test, showing increasing pulse amplitudes over time[2]. Time is represented in the X-axis, and current is in the Y-axis.

B. Software Development

A custom Python-based program was developed to configure and operate the Keithley instruments. The software implements several key features. Our program utilizes the PyVISA library to establish and manage communication with the Keithley 6221 and 2182A over an Ethernet connection. The program allows for configuring both pulsed IV sweeps and DC linear staircase sweeps. The program collects and processes measurement data from the 2182A. The program enables precise timing control to synchronize calibration pulses with the accelerator's master timeline by triggering pulse sweeps from an external source. The program stores the collected data in a CSV file and creates graphs of the collected data.

C. Calibration Processes

Two primary calibration test methods were implemented:

1. *Pulsed IV Sweep*

The pulsed IV sweep is designed to calibrate AC-coupled BCMs (ACCTs). This method involves completing several objectives. These include generating a series of current pulses with increasing amplitudes, starting from 0 to 10 mA. Each voltage response from the BCM needs to be measured by the Keithley 2182A. Once this is complete, the measured voltage data must be collected, stored, and compared with the known injected current. The pulse delta mode is configured on the Keithley 6221 and the Keithley 2182A to perform this test. A bottleneck of the timing of this test is the reliance on power line cycles (PLC). Every pulsed delta measurement takes place over the interval of a minimum of 5 PLCs. Keithley sets this limit for this particular measurement mode[2]. Figure 4 illustrates the timing of the pulsed delta test. Figure 3 represents a diagram of a pulsed delta sweep, with currents increasing in amplitude over time.

2. *DC Linear Staircase Sweep*

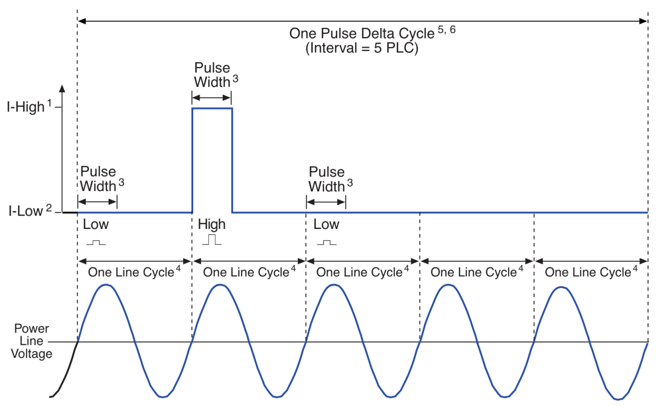
A linear staircase sweep is a method that is best used for calibrating DC-coupled BCMs (DCCTs). This method entails the completion of some objectives. These include generating a continuous current that increases in a stepwise manner. Each of these current steps must be maintained for a short duration to allow for a measurement to be taken. The DC linear staircase sweep must be completed within the 66.63 ms gap between Linac pulses in the 15 Hz cycle. The Keithley 2182A must measure the BCM response at each current step.

Figure 5 shows a DC linear staircase sweep diagram, with current amplitudes increasing over the test duration.

D. Synchronization with Accelerator Timing

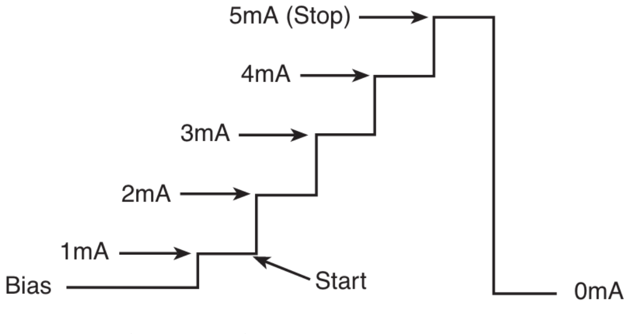
To ensure non-intrusive operation, the calibration system must be synchronized with the accelerator's master timeline. This is achieved by utilizing a Multi-Function Timing Unit to send external triggers to the Keithley trigger link to trigger a pre-configured sweep. Additionally, we programmed the Keithley pair to record a timestamp of every measurement in every test run to ensure test completion in the allotted time gap. This synchronization allows frequent calibration checks without interfering with normal accelerator operations.

Pulse timing



Notes:
1) I-High can be set from -105mA to +105mA (default is 1mA).
2) I-Low can be set from -105mA to +105mA (default is 0mA).
3) Pulse Width can be set from 50µs to 12ms (default is 110µs).
4) One 60Hz power line cycle = 16.667ms (1/60)
One 50Hz power line cylce = 20ms (1/50)
5) With Interval set to 5 PLC (power line cycles):
60Hz: One Pulse Delta cycle = 83.33ms (5/60)
50Hz: One Pulse Delta cycle = 100ms (5/50)
6) Interval can be set from 5 to 999999 PLC (default is 5 PLC).

FIG. 4. This picture details the timing in one cycle of a pulse delta test[2]. Time is represented in the X-axis, and current is represented in the Y-axis.



A. Linear Staircase Sweep

FIG. 5. This represents a linear staircase sweep, with current increasing over time and time represented in the X axis and current in the Y axis[2].

III. RESULTS

Our automated calibration system for Beam Current Monitors (BCMs) successfully implemented both DC linear staircase sweep and pulsed IV sweep methods. The program achieved rapid calibration test times. Some key results are presented for each calibration test method, followed by a comparison of their performance.

A. DC Linear Staircase Sweep Calibration

The DC linear staircase sweep calibration, designed for DC-coupled BCMs (DCCTs), achieved some encouraging results. We successfully completed the DC linear staircase sweep calibration test in 30 ms, well within the 66.63 ms gap between Linac pulses in the 66.7 ms Linac cycle. The sweep covered a current range of 0 mA to 10 mA, providing a comprehensive calibration across the BCM's operational range. This was done in four measurements. Voltages were measured at 0, 3.333, 6.666, and 10 mA currents.

Figure 7 shows a graph generated by the program representing measured results from a DC linear staircase sweep calibration test.

B. Pulsed IV Sweep Calibration

The Pulsed IV Sweep calibration test, intended for AC-coupled BCMs (ACCTs), yielded interesting results. Due to hardware limitations, the pulsed IV test speed is limited by the test's reliance on power line cycles as a pulse parameter. The Pulsed IV test uses NPLC (number of power line cycles) as a parameter for the cycle interval. This interval can be set from 5 PLC to 999999 in the Pulsed Delta mode[2]. The entire Pulsed IV Sweep test, consisting of 3 pulses of increasing amplitude and four measurements, was completed in 250 ms. Voltage measurements were taken at applied current levels of 0mA, 3.333 mA, 6.666 mA, and 10 mA. This range of 0 mA to 10 mA covers the typical operational range of the BCM.

Figure 6 illustrates the results of a typical Pulsed IV Sweep test.

C. Comparison of Calibration Methods

The DC linear staircase sweep calibration test method demonstrated successful operation within the time constraints of the inter-pulse gap. Table I summarizes the critical performance metrics of each method.

The DC linear staircase sweep method allows for rapid testing and data acquisition, making it ideal for calibrating DCCTs. The Pulsed IV Sweep method can characterize the dynamic response of ACCTs at a markedly slower rate due to the limitation of the pulsed IV sweep method's reliance on power line cycles.

Both methods demonstrate the capability of our program to perform rapid calibrations. The DC linear sweep method demonstrates the ability to calibrate without interrupting normal accelerator operations, as it can run tests within the time constraints of the inter-pulse gap.

IV. DISCUSSION

The results of our work represent significant progress towards achieving non-intrusive calibration testing. This section will interpret our results in the context of our project objectives, discuss implications for accelerator operations, address current limitations, and outline future directions for this technology.

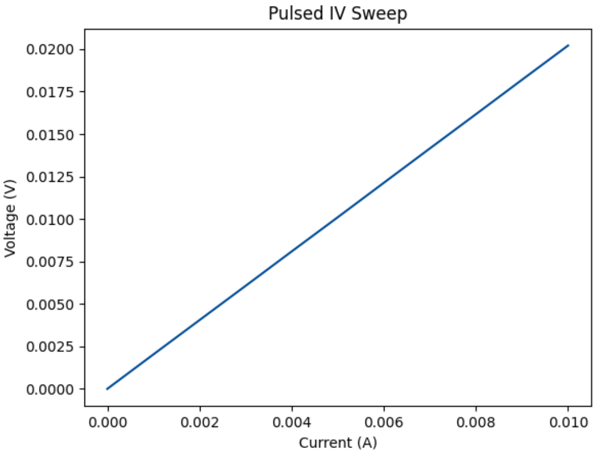


FIG. 6. This graph represents the results of a Pulsed IV Sweep calibration test, showing a voltage response to current pulses of increasing amplitude.

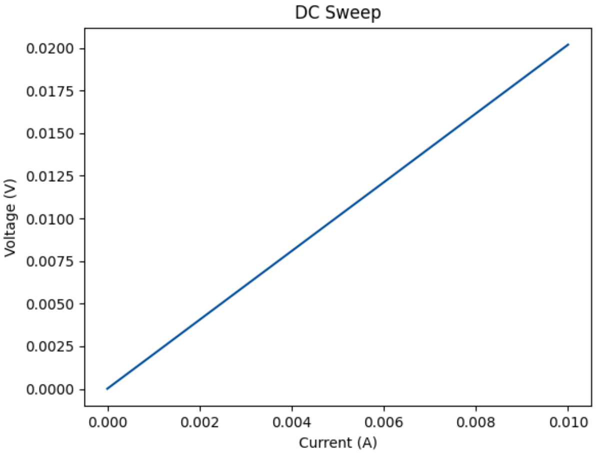


FIG. 7. This graph represents the DC Linear Staircase Sweep calibration test results, showing the voltage response vs. the injected current.

A. Interpretation of Results

The performance of the DC Linear Sweep calibration method exceeded our initial expectations. The Pulsed IV Sweep calibration method needs further work to integrate this method seamlessly into operation.

Achieving test duration times of 30 ms for a DC linear staircase sweep and 250 ms for a pulsed IV sweep demonstrates that our system can operate within the 66.7 ms inter-pulse cycle of the 15 Hz Linac using a DC linear sweep. This DC linear staircase sweep speed allows frequent calibration checks without impacting beam delivery or experimental data collection.

By implementing both DC Linear Sweeps and Pulsed IV Sweeps, our program demonstrates a degree of adaptability to

TABLE I. This table compares DC Linear Staircase Sweep and Pulsed IV Sweep Calibration Test Methods.

Metric	DC Linear Staircase Sweep	Pulsed IV Sweep
Test Duration	30 ms	250 ms
Current Range	0-10 mA	0-10 mA
Number of Data Points	4	4
Suitable For	DCCTs	ACCTs

different types of BCMs (DCCT and ACCT). This versatility enables this system to scale to various accelerator facilities and experimental setups.

These results suggest that we have successfully achieved our primary objective of developing a calibration system that can operate without interrupting regular beam operation.

B. Implications for Accelerator Operations

The successful implementation of our automated calibration system has several important implications for accelerator operations. One implication is increased operational efficiency. By eliminating the need for beam interruptions to perform BCM calibrations, our system may significantly improve overall operational efficiency when operating a particle accelerator. This could enable longer, stable experimental run times and potentially faster scientific progress. Additionally, frequent calibrations, made possible by our non-intrusive method, can ensure that BCMs maintain their accuracy over time. This could lead to more reliable beam measurements and improve the quality of any experimental data gathered.

Accurate beam current measurements are crucial for accelerator safety systems. Our system's ability to enable periodic, non-intrusive calibration tests could contribute to safer accelerator operations by ensuring that protective systems always have accurate input data.

By maintaining accurate BCM calibration without beam interruptions, our system could help minimize beam loss by preventing a cascading effect caused by uncalibrated beam current monitors.

These implications highlight the potential of our system not only to improve the specific process of BCM calibration but also to contribute to broader enhancements in accelerator performance and reliability.

C. Current Limitations and Challenges

Although our automated calibration system has shown promising results, it is important to recognize its current limitations.

The nature of working with the time limitation of the inter-pulse gap may limit the complexity of calibration tests that can be performed. More sophisticated calibration algorithms may require longer time windows.

The current system has been tested with a maximum current of 10 mA. Some accelerator applications may require calibration at higher current levels, which would require some program modification. This might necessitate the implementation of different measurement instruments. Additionally, this study has not fully characterized the impact of environmental factors, such as temperature fluctuations or electromagnetic interference, on the calibration process.

While the system has demonstrated a successful proof of concept test run for a single BCM, scaling it to calibrate multiple BCMs in a large accelerator facility simultaneously may present additional challenges. Addressing these limitations will be crucial to the automated calibration system's broader adoption and long-term success.

D. Future Work

Several avenues for future work emerge based on our results and current limitations. One such avenue is developing the capability to calibrate multiple BCMs simultaneously, potentially using a multiplexing system to switch between monitors during the inter-pulse gap. Another goal for future improvement is to fully integrate the calibration system with the existing accelerator control infrastructure to allow for automated, on-demand calibration as part of routine operations.

Investigating the potential of applying similar non-intrusive calibration techniques to other accelerator diagnostic tools beyond BCMs could provide valuable insights.

Finally, a long-term study to evaluate the system's performance over extended periods of accelerator operation, including its impact on beam stability and experimental data quality, should be done to ensure the efficacy of our program.

These forward-looking goals aim to build upon the current system's success, address its limitations, and expand its capabilities to further enhance accelerator operations and scientific productivity.

V. CONCLUSION

This study presents the successful development and implementation of an automated calibration system for Beam Current Monitors (BCMs) in particle accelerators. Our system addresses the critical need for frequent and accurate calibration without interrupting regular beam operation.

Key achievements of this work include the development of two calibration methods: a DC Linear Staircase Sweep and a Pulsed IV Sweep, addressing the need for calibration of multiple types of BCMs. The backbone of this program that enabled these calibration methods was the development of a flexible, Python-based control system for precise current injection and measurement. The demonstration of rapid calibration times (30 ms for the DC Linear Staircase Sweep) that fit within the 66.6 ms inter-pulse gap in the 15 Hz Linac cycle is a critical accomplishment of this work, enabling the functionality of calibration during operation. Additionally, the added functionality of the calibration program, which can be triggered remotely with a multi-function timing unit, allows integration of this program into the master timeline.

The implications of this automated calibration system extend beyond mere technical improvements. By enabling more frequent and non-intrusive calibrations, this system has the potential to significantly enhance accelerator operational efficiency, improve measurement reliability, contribute to safer operations, and reduce beam loss. These benefits collectively support more productive scientific research in high-energy physics and related fields.

Although current limitations, such as the fixed time window and tested current range, present opportunities for future work, the system that this work developed represents a significant step forward in accelerator instrumentation. Future works, including multi-BCM calibration capabilities and integration with broader accelerator control systems, promise to expand the impact of this technology further.

In conclusion, this automated calibration system for BCMs demonstrates the innovative potential of these instruments to address challenges in accelerator operations. By enabling more precise, frequent, and non-intrusive calibrations, this work contributes to the broader goals of improving accelerator performance, enhancing experimental data quality, and advancing our collective understanding of physics.

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- pyvisa/pyvisa-py
- NumPy
- matplotlib

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[1] R. C. Webber, en“Tutorial on beam current monitoring,” in en*AIP Conference Proceedings*, Vol. 546 (AIP, Cambridge, Massachusetts (USA), 2000) pp. 83–104, iSSN: 0094243X.

[2] K. I. Inc, en“Model 6220 DC Current Source Model 6221 AC and DC Current Source Reference Manual,” (2008).

[3] K. I. Inc, en“Model 2182A Nanovoltmeter User’s Manual,” (2022).

[4] K. I. Inc, “Low-Level Pulsed Electrical Characterization with the Model 6221/2182A Combination,” (2004).