Noise Reduction for ALPHA-g Magnet Control System

CERN Summer Student Deliverable

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I. INTRODUCTION

According to the Standard Model and CPT theory, antimatter and matter should have been made in equal amounts during the Big Bang, but the world we live in is only regular matter. By comparing the precision of hydrogen measurements to that of antihydrogen ($\overline{H}$), experiments can put limits on CPT and refine current theory [1]. The **A**ntimatter **L**aser **PH**ysics **A**pparatus (ALPHA) at CERN's Antiproton Decelerator (AD) Hall is currently studying this phenomenon by mixing antiprotons from the Proton Synchrotron with positrons generated from Na-22 to create and trap antihydrogen [2]. ALPHA consists of two experiments: ALPHA-2, which specializes in antihydrogen spectroscopy using lasers, and ALPHA-g, which studies the affects of gravity on $\overline{H}$.

In 2023, ALPHA-g published preliminary results showing antihydrogen fell with the same gravitational acceleration as hydrogen [3]. Currently, ALPHA-g is undergoing upgrades to make this measurement more precise. To make better measurements, precision magnets are being added to the apparatus in addition to other upgraded hardware. These new magnets, in addition with all the other ALPHA magnets, are controlled by the Magnet Control System (MCS) as shown in Figure 1 [4].

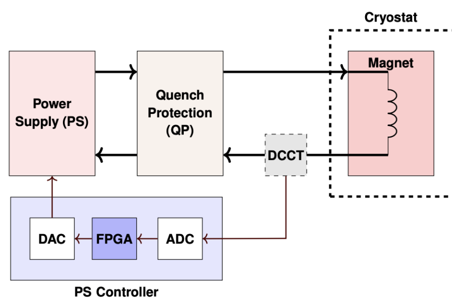


FIG. 1: *ALPHA Magnet Control System. Figure from J. Singh. Fundamental Tests of Antimatter Gravitation with Antihydrogen Accelerators [4].*

In the figure above, the PS controller consists of two compact RIOs (cRIOs) acting as a PID controller to modulate the current in the superconducting magnets. The signal is sent to the power supply (PS), which then sends a signal to the Quench Protection System (QPS). The QPS is able to keep the entire system safe if the magnet quenches by distributing heat throughout several circuit elements. Assuming no quenches are occurring, the current from the QP is sent to the magnet to control the magnetic field in the apparatus. The current in the magnet is measured using a direct current-current transformer (DCCT), which sends the signal back into the PS controller. Since it is also a PID controller, any deviations in the measured current from the expected current is fixed, and a new signal is sent out again [4].

Unfortunately, physics is still unable to predict exactly when a superconducting magnet will quench. Thus, the MCS must be sensitive enough to detect even the slightest change in current in the system to activate the QPS in time to protect the rest of the system. This means the MCS is very sensitive to noise, and unfortunately, adding new magnets during upgrades to the system adds more noise. To keep noise to a minimum regardless of the magnets in the system, a circuit can be introduced between the DCCT and PS controller. This circuit will have a relatively low current because the magnet will be superconducting while the system is on, and when introduced, must not add any more noise to the system. The goal for this summer was to design, build, and test the noise-reduction abilities of this circuit in a mock MCS setup.

II. METHODS

After careful inspection of spec sheets for component compatibility for the system, the circuit shown in Figure 2 was designed for noise reduction to the MCS.

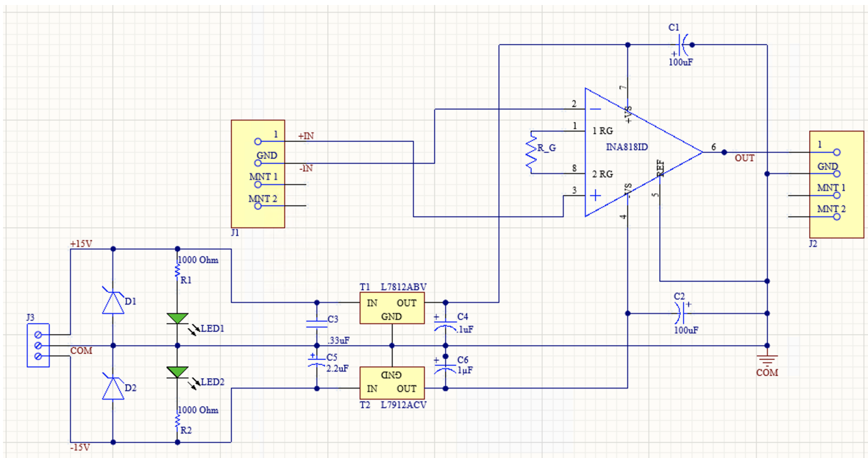


FIG. 2: *Noise reduction circuit diagram.*

The circuit can be divided into two sides; the right hand side (RHS) with the IC chip, and the left hand side LHS with the voltage regulators, LEDs, and zener diodes.

The LHS of the circuit acts as circuit protection from overvoltage or reversed polarities. The voltage from the terminal block J_3 comes from two single output DC power sources wired to produce $\pm 12V$. The voltage regulators T_1 (Part L7812ABV) and T_2 (Part L7912ACV) are functional up to $\pm 15V$, and keep voltage entering the RHS to $\pm 12V$. The voltage regulators are in parallel with decoupling capacitors C_3, C_4, C_5, and C_6 which stabilizes the voltage exiting the regulators by reducing high frequency noise and controlling severe voltage increases or drops. To protect the circuit from polarity reversals, two zener diodes are included. There are also two LEDs LED_1 and LED_2 and current-limiting resistors R_1 and R_2; the LEDs are indicators the circuit is powered by the DC power source correctly.

The output from the LHS acts as the power to pins 4 and 7 of the IC chip (Part INA818D) on the RHS, which performs the noise reduction. Current from the DCCT enters the circuit via the BNC connector J_1 and feeds into the IC chip. No resistor R_G is included to keep the gain of the amplifier to $G = 1$, although space on the perf board was left for future use of R_G. Two decoupling capacitors C_1 and C_2 are included to isolate the AC output signal from the rest of the circuit to reduce noise. Output from the circuit goes to the BNC connector J_2, and is connected to the cRIO for data collection.

This circuit was constructed on a perf board. The LHS was built and tested first to ensure the voltage output was no more than $\pm 12V$ before building and testing the RHS noise reduction circuit. Once the circuit was finished, a function generator was used to generate a test sine input signal and the output was sent to an oscilloscope.

With the circuit fully constructed and confirmed to work, it was included in a mock MCS setup. The test used cRIOs for input signals to the PS and output signals from the DCCT. Six different settings were used: a cRIO output of $0A$, $\pm 10A$, and $\pm 50A$, and a PS output of $0A$. For each setting, three readings for 5 seconds each were recorded and later averaged to find the average voltage output from the DCCT with and without the circuit. Using a scalar factor of 125 Amps = 10 V (a feature of the DCCT), the current through the DCCT was calculated and compared to the current inputted by the cRIO or PS. In addition to reading the output of the DCCT, the cRIO also calculates a Fast Fourier Transform (FFT) of the noise output from the system to determine any significant frequencies introduced in the setup.

III. RESULTS AND DISCUSSION

The final circuit board for testing is shown in Figure 3. With the voltage protection circuit working and the IP chip producing no noticeable effects on the output as shown on the scope in Figure 4, tests on the MCS test setup could begin.

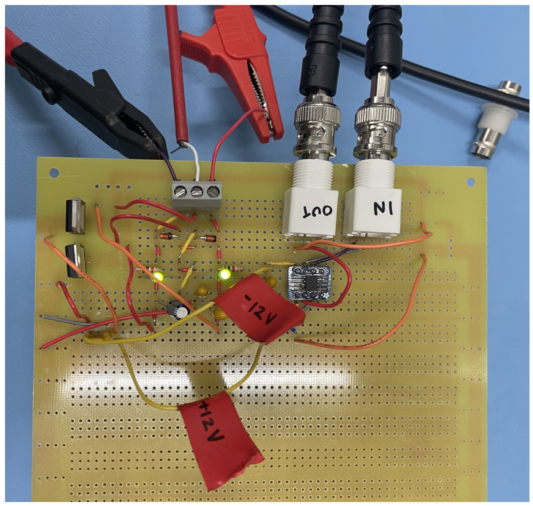


FIG. 3: *Final circuit under preliminary tests. Input is from a function generator, and the output is sent to the oscilloscope in Figure 4.*

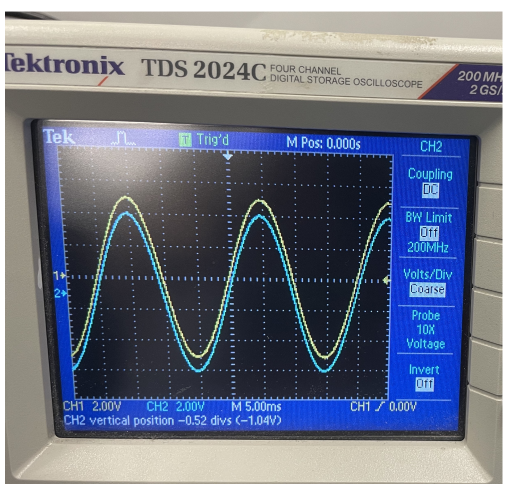
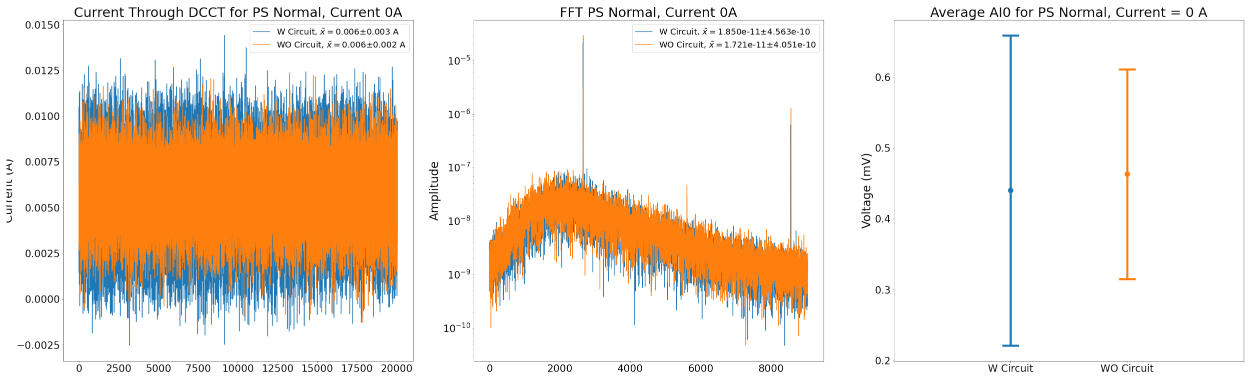


FIG. 4: *Scope measuring input signal from function generator (yellow trace) and output signal from circuit (blue trace). Signals are purposely offset for visualization.*

The results of Test 1 (cRIO input and output) are shown below for $0A$ from the PS and $-10A$ from the cRIO. The rest of the plots can be found in the Appendix.

The following are the results for $0A$ of current from the PS. The average current output from the DCCT without the circuit was $.006 \pm .002$ A and the average output with the circuit was

$.006 \pm .003$ A. Although there was no current input to the system, there may have been a current output reading because of a DC offset somewhere in the equipment. Adding the circuit reduced the noise in the system by 4.968%. However, there was significant overlap between the standard deviation of the output without the circuit over the average output with the circuit as shown in Figure 5c, indicating the circuit may not have significantly impacted the output of the circuit. Based on the FFT in Figure 5b, the circuit did not introduce any significant frequencies to the system.



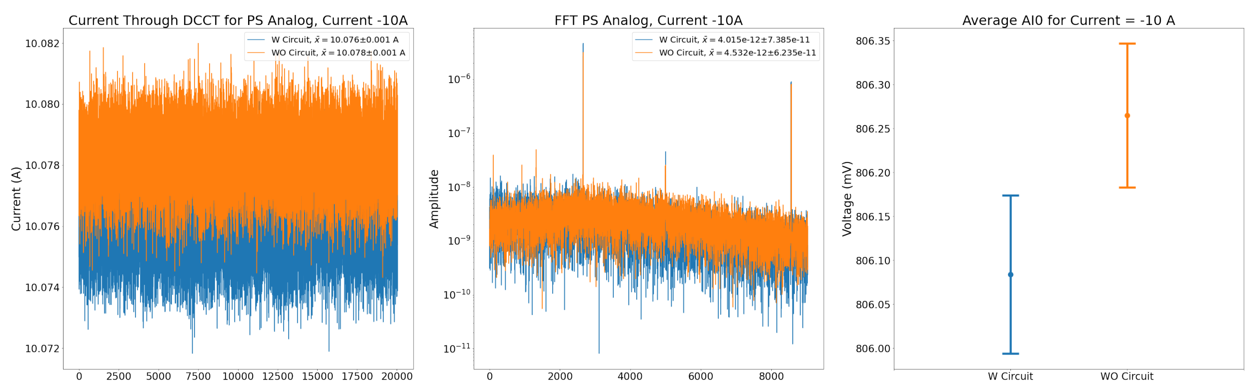
(a) *Current output from DCCT with and without circuit.*

(b) *FFT measurements with and without circuit.*

(c) *Average DCCT output with and without circuit.*

FIG. 5: *Results for 0A when PS controls current. W = with, WO = without.*

The results for $-10A$ controlled by the cRIO are below in Figure 6.



(a) *Current output from DCCT with and without circuit and -10A.*

(b) *FFT measurements with and without circuit at -10A.*

(c) *Average DCCT output with and without circuit at -10A.*

FIG. 6: *Results for -10A when cRIO controls current. W = with, WO = without.*

The average output without the circuit was $10.078 \pm .001$ A and the average with the circuit was $10.076 \pm .001$ A. The difference in noise in Figure 6a with and without the circuit is much clearer to see compared to Figure 5a, although the percent decrease of noise with the circuit is .0224%. However, the standard deviation of output without the circuit did not overlap with the average output with the circuit, indicating the values are significantly different, so there was a noise decrease. There is a frequency spike with the circuit around $3000Hz$, but $-10A$ is the only current at which this spike occurred, indicating this frequency came from the system rather than the circuit itself.

The percent decrease of the noise using the circuit at different currents is shown in Table I. The most noise reduction occured when the current into the system was 0A; when the PS controlled the current at 0 A, the noise reduction with the circuit was best, with a 4.968% decrease of noise. On the other hand, -10 A inputted to the system had the least amount of noise reduction of .0029% with the circuit included. This may have occurred if the IC chip had a small amount of leakage output current that added to the current from the DCCT, thus raising the total output current into the cRIO. This would have increased the noise in the system, making it closer to the noise in the system without the circuit. To further test this, two additional decoupling resistors will be added to the positive and negative input pins to the IC chip to ensure the current out of the chip will be 0 A.

Current Settings	**Percent Decreases**
0 A, PS Controlled	4.968%
0 A, cRIO Controlled	2.533%
+10 A	.0221%
-50 A	.0067%
+50 A	.0039%
-10 A	.0029%

TABLE I: *Percent decrease of noise in system with circuit included, in order from most effective at noise reduction to least.*

IV. CONCLUSIONS AND PERSPECTIVES

With each test current, the noise in the system reduced with the circuit included in the system. However, several further tests are needed to be conducted to determine the effectiveness of this circuit, but first, two decoupling resistors would be added on the plus and minus input pins of the IC chip to ensure the current leaving the circuit is kept to 0A.

The next test will test how the PS controls the current through the system without cRIOs. The same currents of $0A$, $\pm 10A$, and $\pm 50A$ would be used, for both with and without the circuits. This time, since the cRIOs were not used, visual readings from the digital multimeter will be recorded for approximately 3 minutes and averaged to determine the voltage output from the DCCT. An additional test would test how the digital multimeter and cRIO in the same system influence the current. ALPHA has noted instances of voltage shifting when multiple output devices were included in the system, so having a digital multimeter and cRIO reading the current would help get a definitive measurement of the voltage shift. The output from the DCCT would go to both the digital multimeter and the cRIO. The same currents directly controlled by the PS of $0A$, $\pm 10A$, and $\pm 50A$ will be used, with and without the circuit.

Once it is understood how the circuit impacts the system noise levels with different measurement-reading devices, the circuit will be installed to the ALPHA-g MCS and tested before running the full gravitational experiment.

V. ACKNOWLEDGEMENTS

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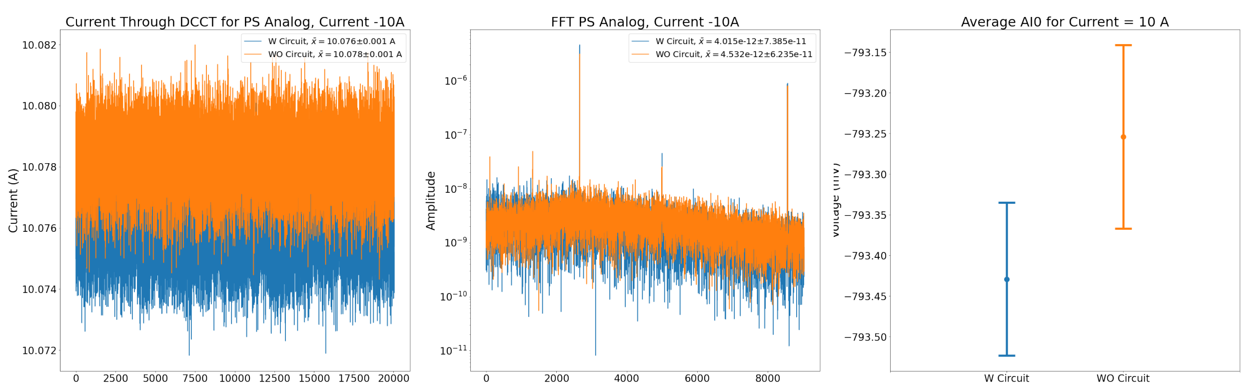
VI. APPENDIX

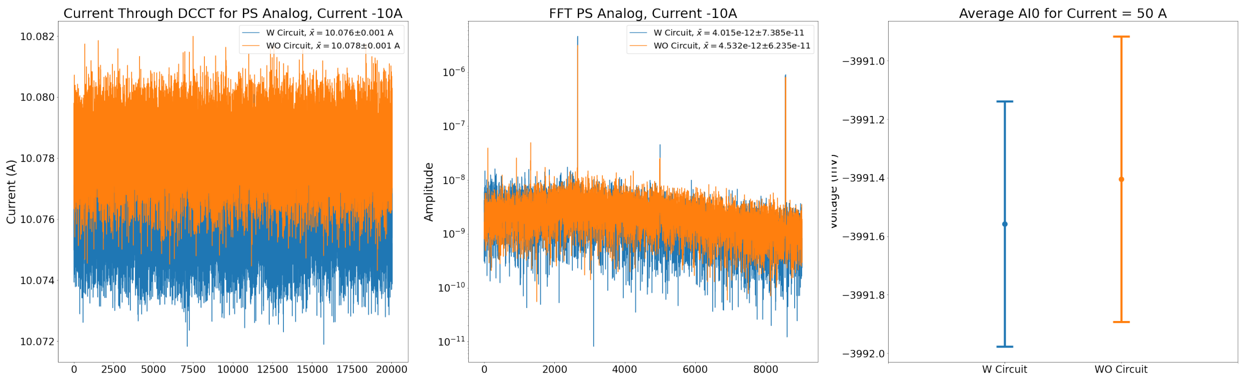


(a) *Current output from DCCT with and without circuit and +10A.*

(b) *FFT measurements with and without circuit at +10A.*

(c) *Average DCCT output with and without circuit at +10A.*

FIG. 7: *Results for +10A when cRIO controls current. W = with, WO = without.*

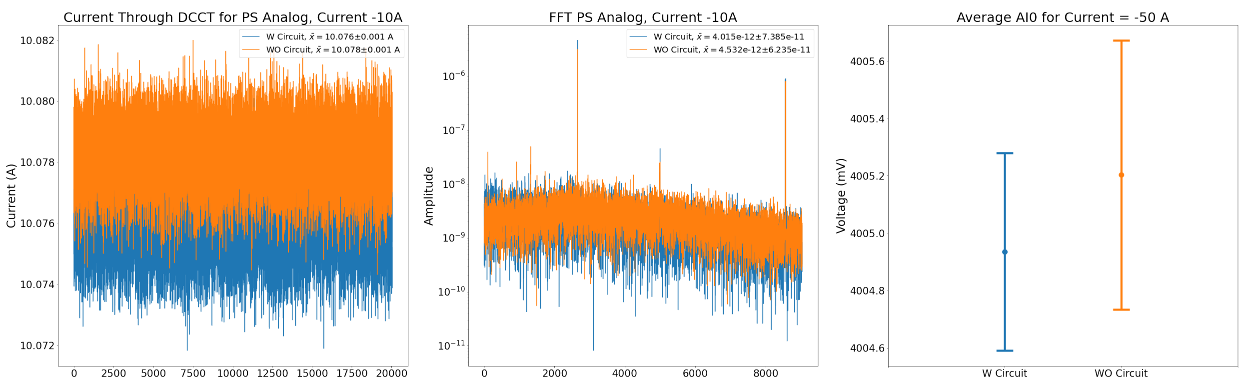


(a) *Current output from DCCT with and without circuit and +50A.*

(b) *FFT measurements with and without circuit at +50A.*

(c) *Average DCCT output with and without circuit at +50A.*

FIG. 8: *Results for +50A when cRIO controls current. W = with, WO = without.*

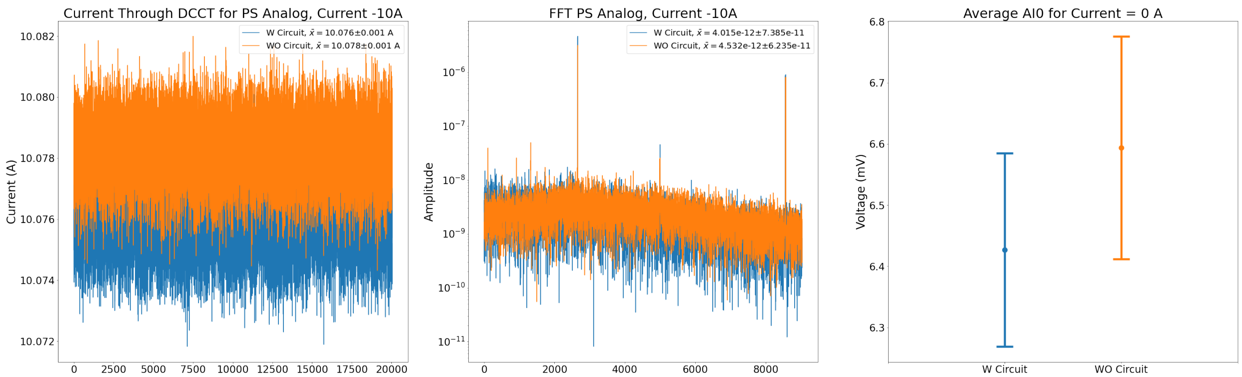


(a) *Current output from DCCT with and without circuit and -50A.*

(b) *FFT measurements with and without circuit at -50A.*

(c) *Average DCCT output with and without circuit at -50A.*

FIG. 9: *Results for -50A when cRIO controls current. W = with, WO = without.*



(a) *Current output from DCCT with and without circuit and 0A.*

(b) *FFT measurements with and without circuit at 0A.*

(c) *Average DCCT output with and without circuit at 0A.*

FIG. 10: *Results for 0A when cRIO controls current. W = with, WO = without.*