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Data management: Caesium fountain

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Abstract

Atomic clocks, leveraging atomic oscillations in elements like rubidium and cesium-133, offer unprecedented precision in timekeeping, crucial for defining the second in the International System of Units. Among them, the caesium fountain atomic clock stands out, capable of maintaining accuracy within less than a second over millions of years. This extraordinary precision is essential not only for global timekeeping and satellite navigation but also for cutting-edge scientific research. At CERN, the Alpha experiment uses the caesium fountain clock to meticulously measure the transition frequencies of anti-hydrogen and compare them with regular hydrogen. Such comparisons are fundamental to investigating the matter-antimatter asymmetry suggested by the Big Bang theory. If a discrepancy in transition frequencies is found, it could reveal new physics, shedding light on why the observable universe is dominated by matter. This project focusses on improving the accessibility and management of caesium fountain hyperfine structure data by integrating it into a sophisticated database Midas, via LabVIEW. Facilitating data flow will improve analysing efficiency, allowing for more precise study on anti-hydrogen and other applications in fundamental physics.

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1 INTRODUCTION & THEORETICAL BACKGROUND

Atomic clocks provide the highest level of timekeeping precision, utilising atoms' unique qualities to measure time with unparalleled accuracy. Atomic clocks, unlike conventional clocks powered by quartz crystals or mechanical mechanisms, rely on atomic oscillations of materials like rubidium or cesium-133 (Betts, 2024). Such oscillations can be observed thanks to the discovery of Laser cooling which allowed for the observation of specific transitions in such atoms (Wynands & Weyers, 2005). These clocks operate on the resonance frequency, which is typically in the microwave region, at which atoms change to transition to a different energy levels.

The International System of Units defines a second as a fundamental measure of time that is carefully controlled by the frequency of atomic clocks. Atomic clocks have improved technologically since its inception in 1967, when the caesium standard defined a second as 9,192,631,770 vibrations. Modern variants, such as caesium fountain atomic clocks, may retain time precision over millions of years with an accuracy loss of less than a second (Fortier, 2023). Their extraordinary accuracy is critical for worldwide timekeeping standards, as well as satellite navigation systems, telecommunications, and advanced scientific research, such as accurately and precisely determining anti-hydrogen transition frequencies.

The Caesium fountain operates using Caesium atoms, which are initially pure and thermally vaporized. These atoms are collected using magnetic fields and other optical traps before being laser-cooled into a "ball" or cloud of atoms using the optical molasses process. This technique uses six lasers for doppler cooling, two on each axis (x, y, and z). The laser cooling technique brings the Caesium atoms to only a few μK above absolute zero and thus at very low speeds (Wynands & Weyers, 2005).

Once cooled, the Caesium cloud is launched into the air by one of the laser pairs, and the six cooling lasers are turned off. As the cloud ascends and lowers due to gravity, it passes through a microwave cavity twice: once on the way up and once on the way down. The microwave interacts with the caesium atoms, causing some to caesium atoms to be excited to higher energy levels. Following that a detecting laser detects the number of excited caesium atoms.

The microwave frequency is modified until resonance is established, which means that it matches the transition frequency needed to excite the Caesium atoms to a higher energy state. The detection laser confirms resonance by recording the microwave frequency that excites the most Caesium atoms.

It is important to notice that the cloud of caesium atoms passes twice through the microwave cavity; this technique is known as the Ramsey method, and it improves on the Rabi method. The Ramsey approach increases the precision of frequency measurements. By allowing the atoms to traverse with the microwave field twice, this approach generates an interference pattern that is more sensitive to the specific frequency, allowing for a more precise estimate of the transition frequency (Wynands & Weyers, 2005).

The caesium fountain is a precise time keeping instrument, which is very important for the project Alpha at CERN. After various processes and marvelous experiments, Alpha combines positrons e^+ and anti-protons $\bar{p}$ to form anti-hydrogen $\bar{H}$.

$$e^+ + \bar{p} \rightarrow \bar{H} \tag{1}$$

The anti-hydrogen frequency transitions (for a certain transition) are then studied with high precision using the caesium fountain and compared to regular hydrogen transition frequencies. Because matter and antimatter have the same characteristics but opposite charges, one would expect hydrogen and anti-hydrogen transition frequencies to coincide. Alpha performs such tasks to validate the prediction with high accuracy and precision.

Such an experiment is critical for investigating the big bang theory, which holds that matter and antimatter were generated in identical quantities. Confirming that hydrogen and anti-hydrogen have the identical transition frequency raises the question of where the anti-matter went. However, if Alpha discovers a little variation between hydrogen and anti-hydrogen transition frequencies, it indicates that there is some physics of anti-matter that we do not yet understand, which could help explain where half of the anti-matter went.

The primary aim of this project is to enhance the accessibility of caesium fountain data readings related to the hyperfine structure. By utilizing LabVIEW, we aim to facilitate the efficient transfer of this data to a more sophisticated database. This process is expected to streamline data management and analysis, ultimately improving the usability and availability of the hyperfine structure data for research on anti-hydrogen and other applications.

2 MATERIALS & LIBRARIES

The project was primarily implemented using code, with LabVIEW serving as the main development environment. LabVIEW is a graphical programming language that allows us to create and manage the project's functionality through a visual interface. Additionally, GitHub was utilised for version control and collaborative development, enabling us to store and manage various stages of the project efficiently. Moreover the Pico-TC-08 data logger was used to obtain temperature data as shown in figure 1.

Fig. 1. the pico TC-08 is a thermocouple data logger that allows us store data relating temperatures.

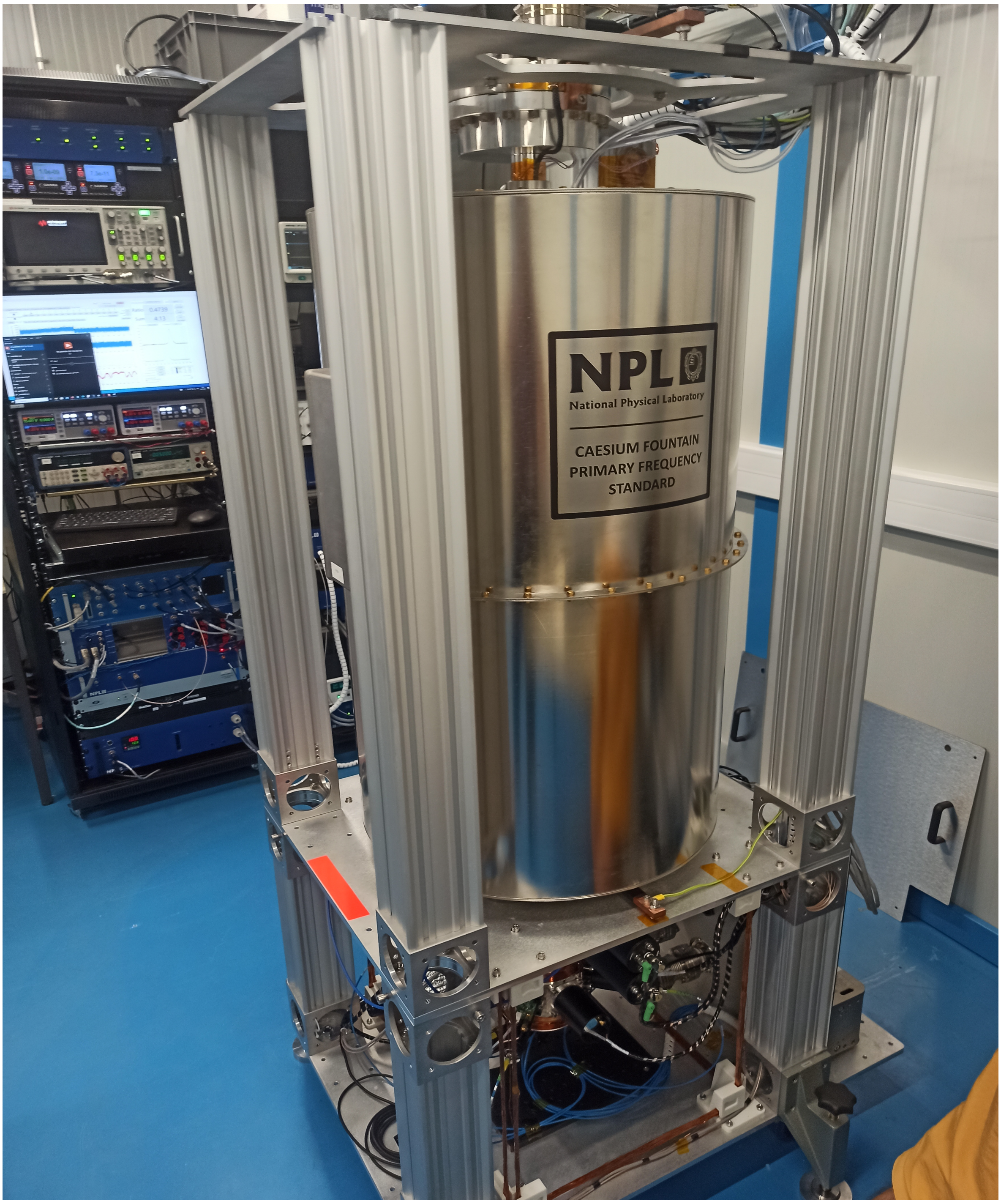

Fig. 2. The Caesium Fountain at CERN. The silver cylinder serves as a housing for magnetic shielding, preventing interference from the environment. At the bottom, there are six lasers and an equipment that thermally vaporises caesium (see figure 3)

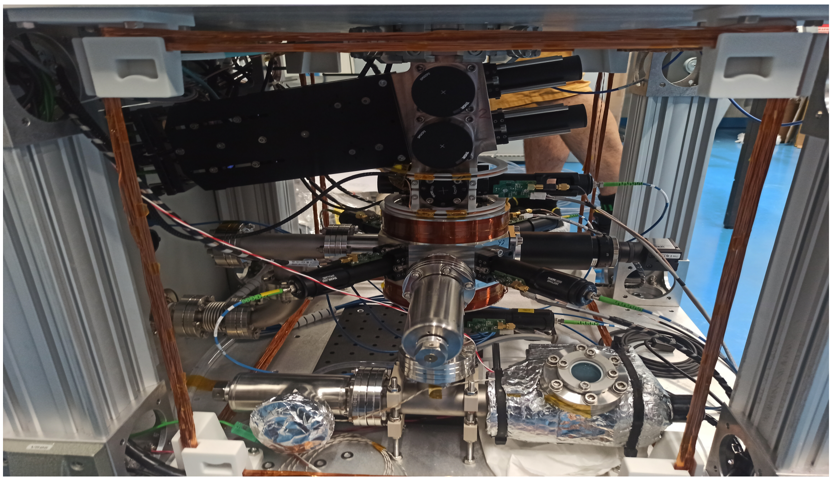

Fig. 3. Six lasers (blue wires with green stripes) are used for optical molasses and manipulation. At the bottom, the instrument for thermally vaporizing caesium atoms is visible. The copper cylinder houses a Helmholtz coil, which generates a magnetic field to trap the atoms based on their magnetic properties,

Fig. 4. The computer that controls the caesium fountain. At the top, there are three indicators displaying pressures: 7.0×10^{-10}, 9.9×10^{-10}, and 7.4×10^{-11}, these correspond to vacuum levels of the caesium fountain.

3 METHODOLOGY

Initially, a virtual space (virtual PC) was created to avoid faults that could disrupt the operation of the caesium fountain. LabVIEW was downloaded and installed, and a VI (Virtual Instrument) file was created to collect pressure data from all three vacuum pumps. The pressure values from each vacuum pump were saved in local variables and recorded with a data logger. The current of the vacuum pumps was also measured and logged. Similarly, the TC-08 data logger was used to collect temperature data from the five thermocouples installed throughout the caesium fountain. Furthermore, the thermocouple data was programmed to be saved daily in a new file on the hard drive.

4 RESULTS

Figure 5 shows the LabView setup used to acquire the pressure and current values for the vacuum pumps. The diagram consists of two loops: a while loop and a sequential loop. The sequential loop ensures that parts of the code are executed in a specific order, while the while loop keeps the code on a repeating loop unless some conditions are satisfied. Figure 6 shows the code that was used to log the data acquired by the code shown in figure 5.

Figure 7 shows the code executed to acquire the data via the TC-08 data logger, that is, acquiring the temperatures at certain points in the caesium fountain via the thermocouples. Additionally, the temperature values were stored in the hard disc using the code in figure 8. Moreover, the data was logged in a database using the same code as figure 6, just under different name.

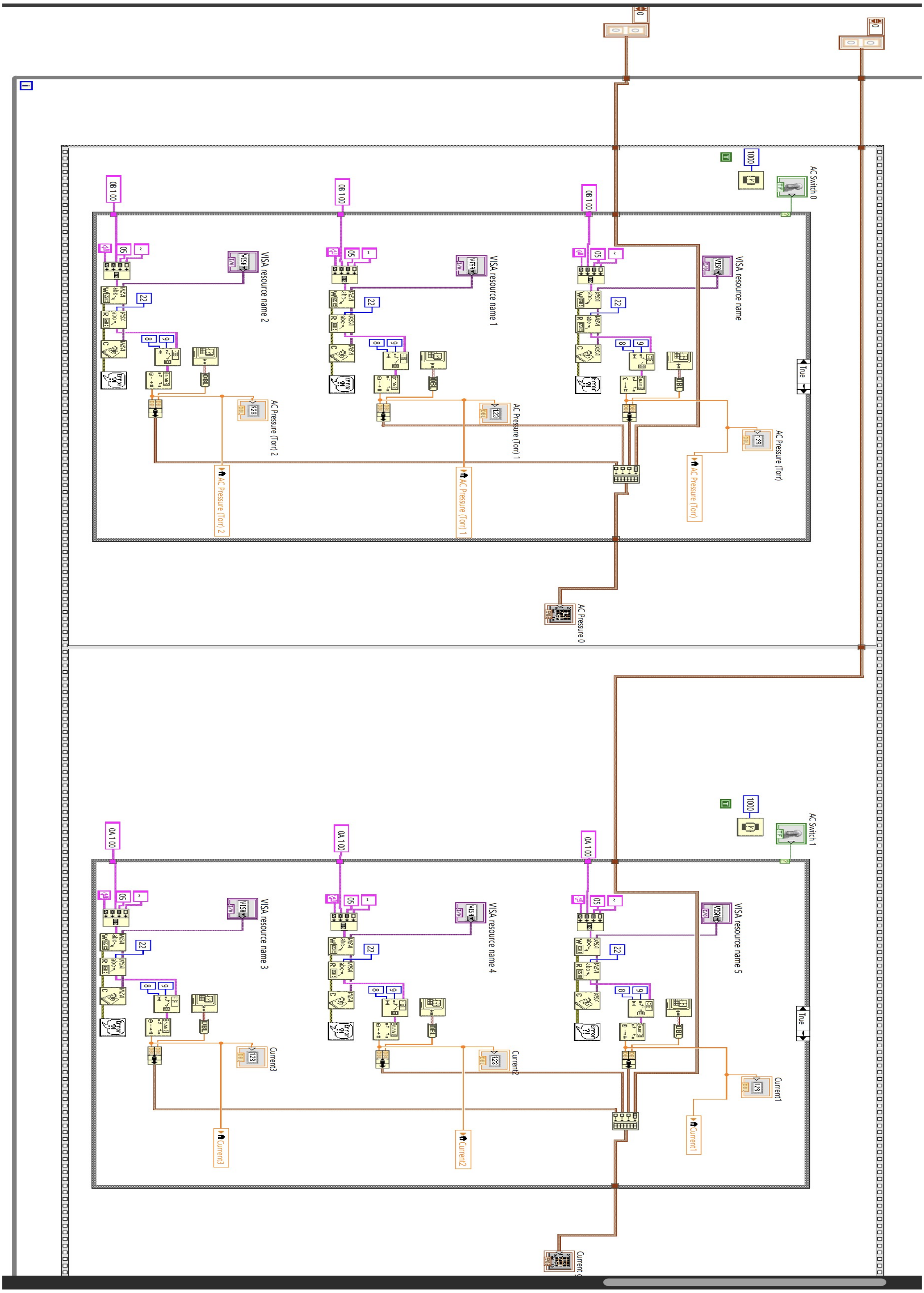

Fig. 5. Pressure-current LabView code

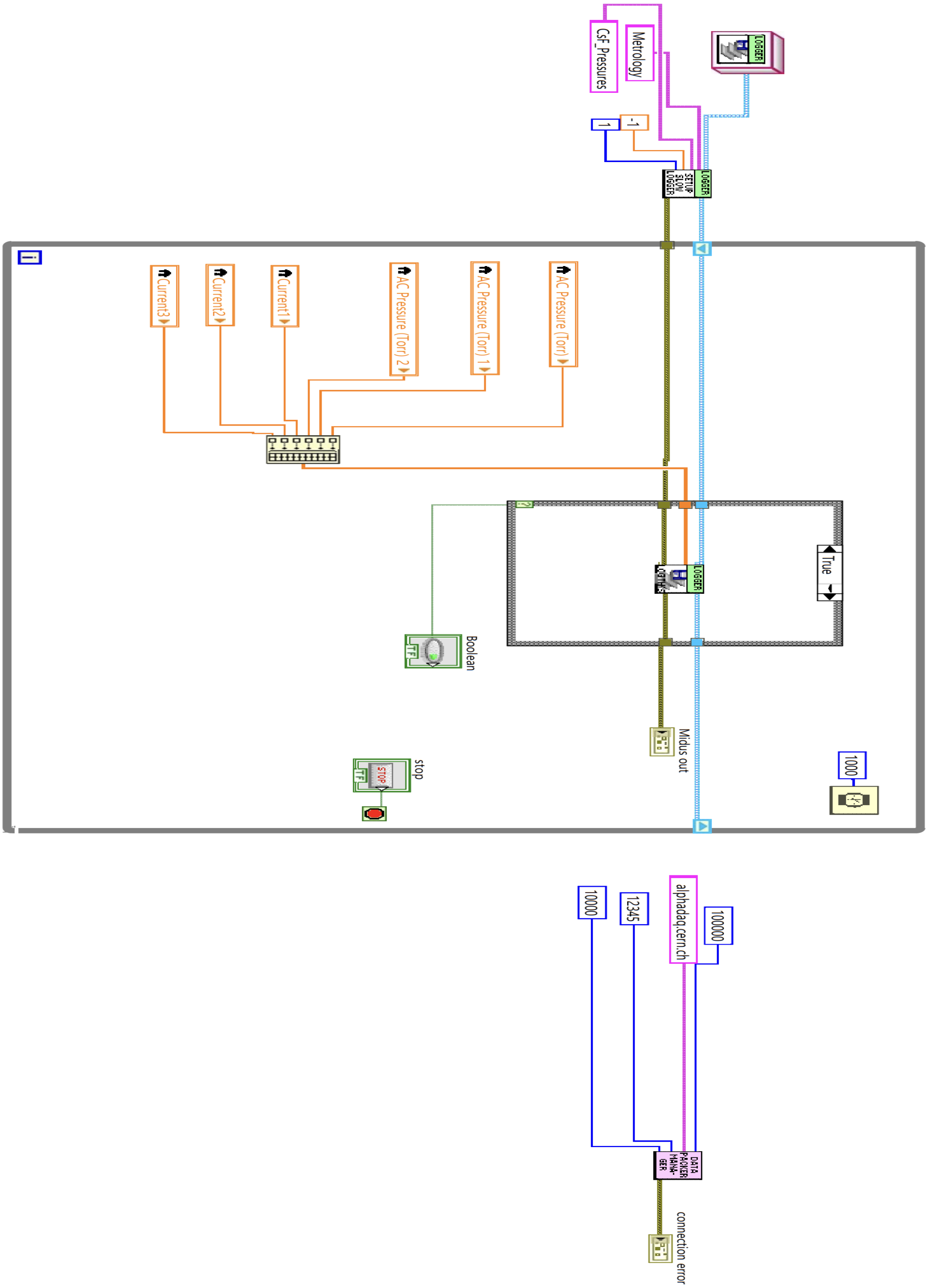

Fig. 6. Data logging into database

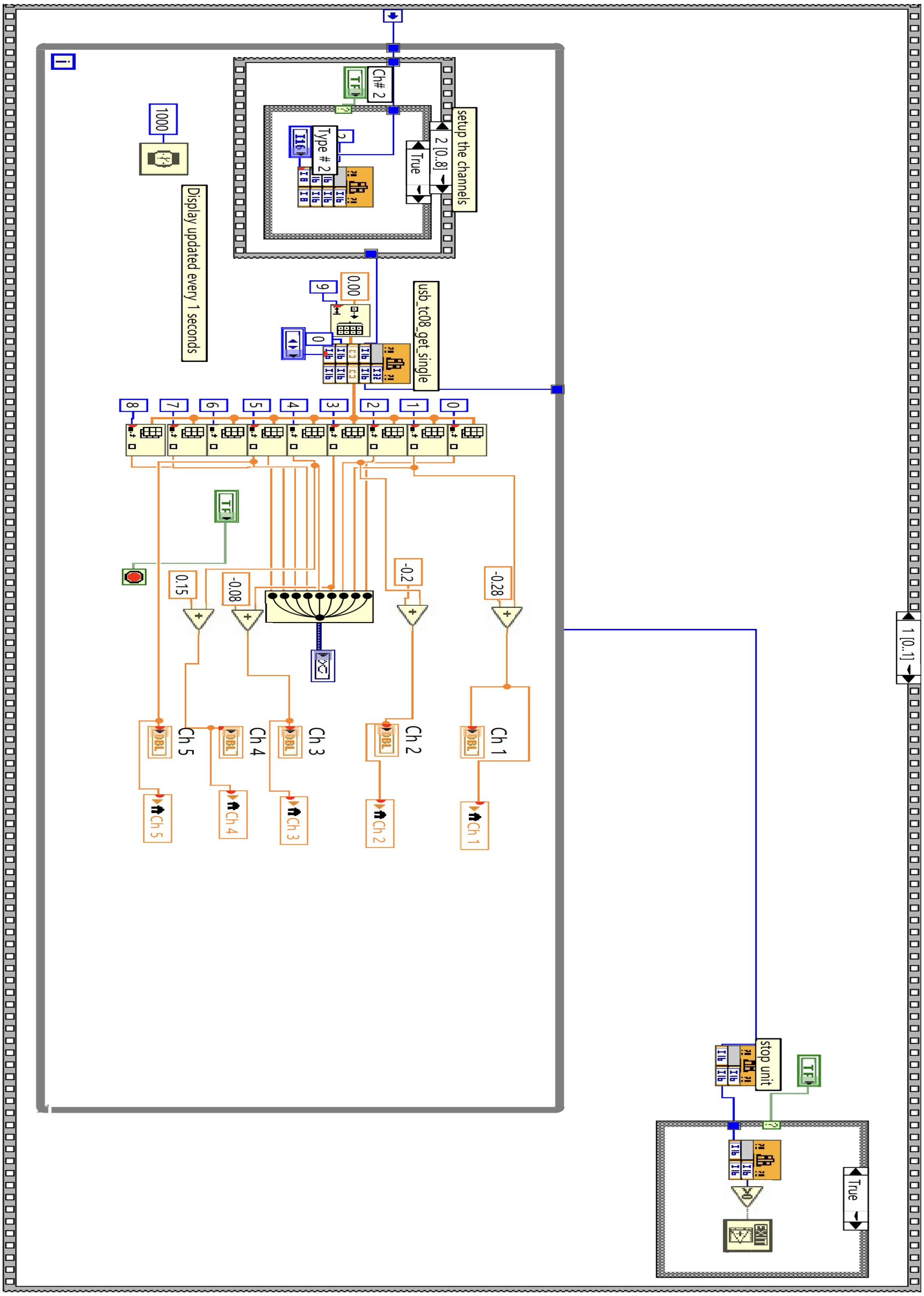

Fig. 7. Acquiring the temperatures via the thermocouples

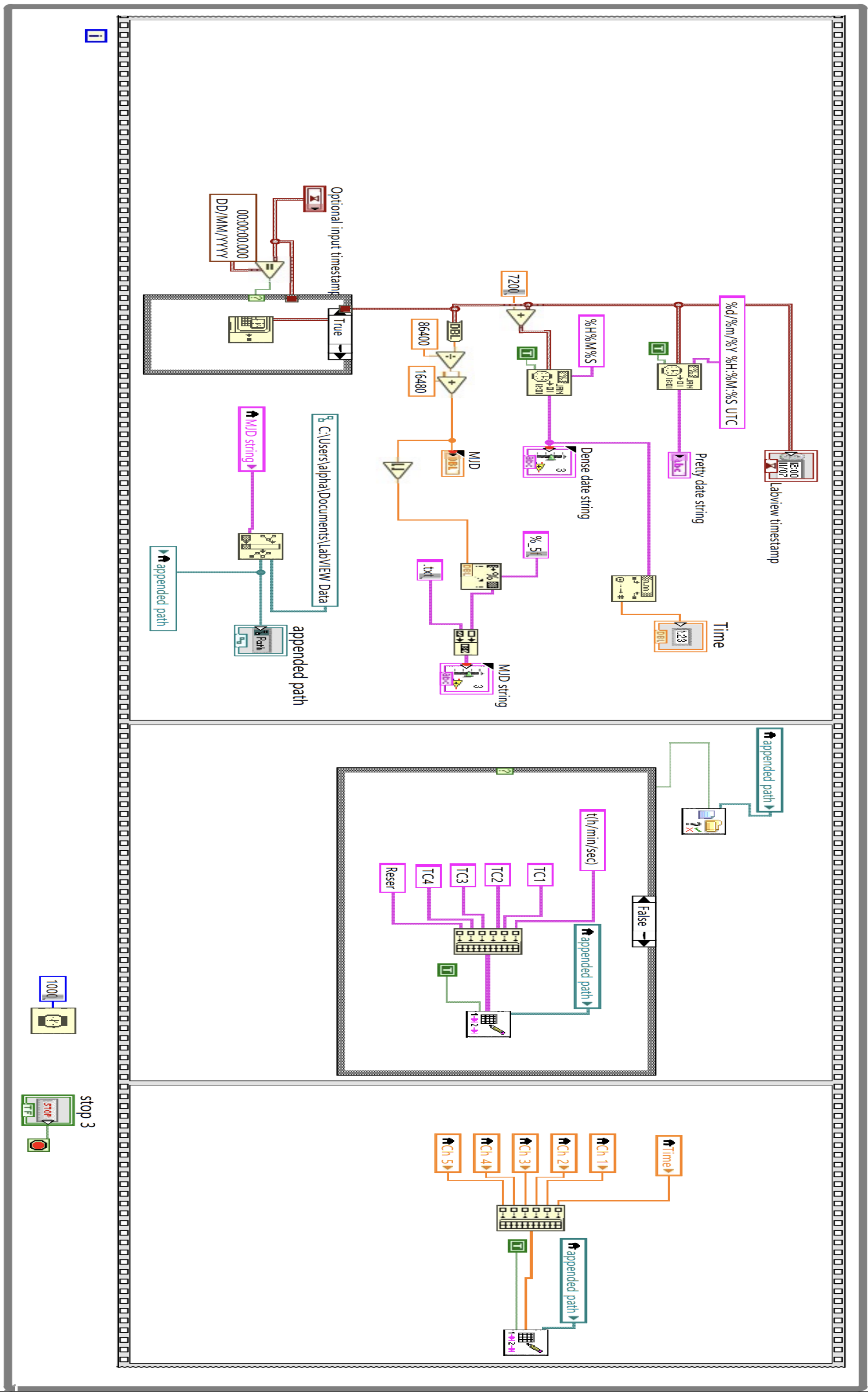

Fig. 8. Data logging of temperature to disc

5 CONCLUSION

The project met its primary goal of improving the accessibility and management of caesium fountain hyperfine structure data by connecting it with the Midas database using LabVIEW. The code created for this purpose was effortlessly implemented, resulting in efficient data flow between the Caesium Fountain atomic clock and the Midas database. This connection dramatically increased the usability and availability of hyperfine structural data, allowing for more efficient and accurate analysis.

As a result of this successful integration, researchers at CERN's Alpha experiment now have more efficient tools for accessing and interpreting critical data on anti-hydrogen frequency transitions. This increase not only improves the precision of present investigations, but it also enables larger applications in fundamental physics research. The improved data management system is an important resource for furthering our understanding of the matter-antimatter asymmetry proposed by the Big Bang hypothesis, and it has the potential to provide new insights into the universe's fundamental principles.

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