Graphical user interface development for streamline testing of concentrator cards

by

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Abstract

The Large Hadron Collider (LHC) at CERN has provided vital information to aid in understanding how particles interact. One of the latest achievements was the discovery of the Higgs boson in 2012 by the CMS and ATLAS collaborations at CERN. The Higgs boson was the missing piece of the standard model (SM) of particle physics. However, there are still phenomena that are not explained by the SM that lead researchers to believe there are particles predicted by new theories beyond the SM. Some of these particles can be produced in rare events at the LHC. The upgrade of the LHC for high luminosity operations, so called High Luminosity-Large Hadron Collider (HL-LHC), will allow interactions at higher energy and higher rate. This will result in producing more events of these rare processes and particles, and hopefully, lead to discoveries beyond the SM. The MIP timing detector (MTD) is one of the novel installments in the CMS detector for the HL-LHC operation phase that will allow for precision timing. Concentrator cards (CCs) will be placed in the MTD to communicate between the detector and the data acquisition system by sending timing signals between them. Hundreds of CCs will be assembled and tested at Kansas State University. This thesis discusses the development of a graphical user interface (GUI) that will improve the CC testing process. It will discuss the structure and application of the different modes of the testing process, along with future developments.

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Acknowledgements

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I. Introduction

This thesis discusses the development, structure, and application of a graphical user interface (GUI) created for the improvement of the concentrator cards (CCs) testing process. The CCs are instruments that will be installed during a massive upgrade to the Large Hadron Collider (LHC). This upgrade will allow researchers to search for new phenomena not included in the standard model, as well as indirectly discover new physics through deviations from standard model predictions by improving the precision in measurements of the properties of standard model processes. The standard model is a theory of all the known elementary particles and their interactions with one another described briefly below.

The standard model includes three types of particles: leptons, quarks, and bosons. Leptons are electrically charged electrons, muons, and taus and their respective neutrinos, the electron neutrino, muon neutrino, and tau neutrino. Each pair, i.e., the electron and electron neutrino, of leptons have the same qualities, except for mass and stability. The muon has a larger mass than the electron, the tau lepton even more massive, and neutrinos are nearly massless. For stability, the electron is stable, the muon and tau both decay, and the neutrinos oscillate between the three types. These three sets of leptons and their neutrinos have become known as the three generations of leptons. Quarks are also sorted by three generations, which are the following pairs: up and down quarks, the charm and strange quarks, and the top and bottom quarks. The up and down quarks combine to form protons, neutrons, and other hadrons. The charm, strange, top, and bottom quarks are all unstable and decay. Bosons are the mediators of the fundamental forces. The photon mediates the electromagnetic force, the gluon mediates the strong force, and the W and Z bosons mediate the weak force. The Higgs boson is more unique and mediates the Higgs field interaction with the other elementary particles, which produces particles' masses.[1]

The standard model is an elegant description of the current known elementary particles, but it does not include every particle phenomenon observed. There are theories beyond the standard model that answer some of the remaining questions. The "theory of everything (TOE)"[2] would combine the gravitational force, which is not a particle phenomenon and the only fundamental force not currently incorporated by the standard model, with the electromagnetic, weak, and strong forces in one theory. One idea describing what could lead to the TOE is the graviton particle, a boson mediating the gravitational force. Dark matter is a phenomenon, indirectly observed through gravitational effects, that could also be observed with the LHC. The common trait to these potentially observable phenomena is that each of them needs high energy collisions to be produced. The TOE has "tremendous energies required to verify the existence of the particles predicted by the theory"[2] and various dark matter studies summarized by Vannerom[3] include limits on low energy interactions. The energy at which the protons collide in the Large Hadron Collider (LHC) allows researchers to produce rare high energy interactions in hopes of observing such phenomena.[2,3,4,5]

The LHC, a particle accelerator at the European Organization for the Nuclear Research (CERN), will be upgraded to the High Luminosity-Large Hadron Collider (HL-LHC) to allow for more particle collisions than previous versions. With more particle collisions, researchers will have access to additional rare particle interactions not currently included in the standard model. The minimum ionizing particles timing detector (MTD), a novel precision timing detector, is one of the instruments that will be included on the HL-LHC upgrade. The MTD will include hundreds of concentrator cards (CCs) that will be assembled and tested at Kansas State University. The following pages explain why the HL-LHC upgrade is necessary and how the GUI development will aid in the process of completing the upgrade through an improved testing process of the CCs.[1,6]

II. CMS Detector

The LHC is a 27-kilometer-long particle accelerator at CERN located near Geneva, Switzerland that accelerates protons or nuclei close to the speed of light. Before being sped up, the proton beam is split to create two beams traveling in opposite directions. Then at four specified points along the beamline, the beams are directed at one another for detectors to collect data on the collisions of the particles in the beams. One of which is surrounded by the Compact Muon Solenoid (CMS) detector (Figure i).[6,7]

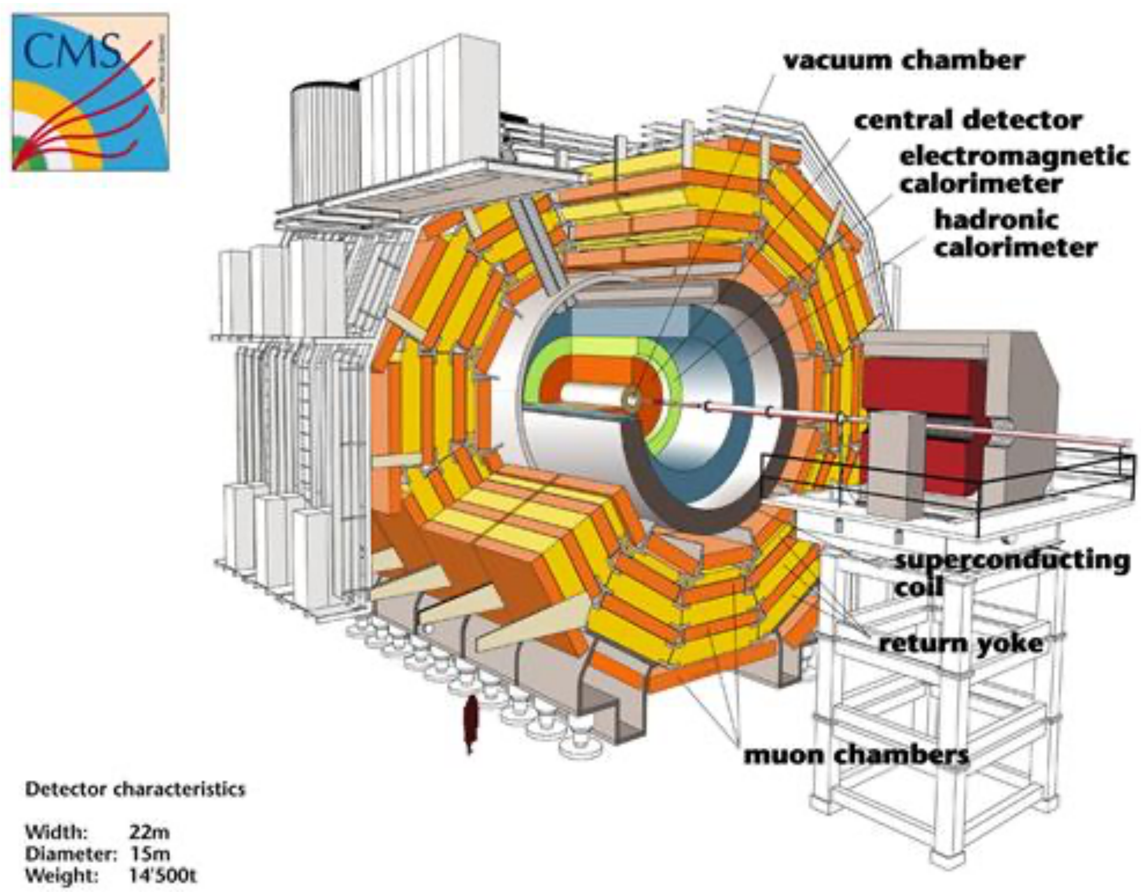

Figure i – Schematic diagram of the various components of the CMS detector thanks to the CMS images gallery.[7]

The CMS detector is called such because in comparison to the ATLAS detector (46 meters long, 25 meters tall), it is compact at 21 meters long and 15 meters tall. Along with the ATLAS detector, the CMS detector is designed to accurately detect and track all particles and uses a powerful solenoid. The CMS detector reconstructs all types of collisions, also called events, that are expected by tracking particles back to a collision point and building a picture of the event. With up to 40 million collisions occurring every second, the CMS detector was built to handle a massive amount of data collecting. Along with collecting the data, The CMS detector accurately detects and tracks particles, which is essential for analyses later.[7,8]

In order to identify a type of particle, the detector's solenoid creates a magnetic field that bends the charged particles' trajectories (Figure ii). This specifically allows the detector to separate positively and negatively charged particles as they bend opposite ways under a magnetic field. While the particles are on their bending paths, the silicon tracker records where the particles are in the detector with an accuracy to 10 micrometers. The particles produce hits on the pixels of the tracker sending electrical signals that are used for the measurement of the transverse momentum. Tracking the particles is important to the reconstruction, along with the recording of particles' energies using dedicated calorimeters for data analysis.[7,8,9]

The detector consists of two calorimeters that record information about the particles' energies. The Electromagnetic Calorimeter (ECAL) stops the electrons and photons from traveling any further in the detector while recording their energies. Similarly, the Hadron Calorimeter (HCAL) records the energies of hadrons and stops their paths. The ECAL allows the hadrons to fly through without much interaction until reaching the HCAL. Neither calorimeter stops muons. The muon trajectory is tracked with muon chambers that also help with determining the momentum and confirm the particle is a muon. Consisting of 1400 muon chambers separated into four layers, the muon detection occurs at the outermost piece of the detector as muons are minimally interacting particles.[7,10]

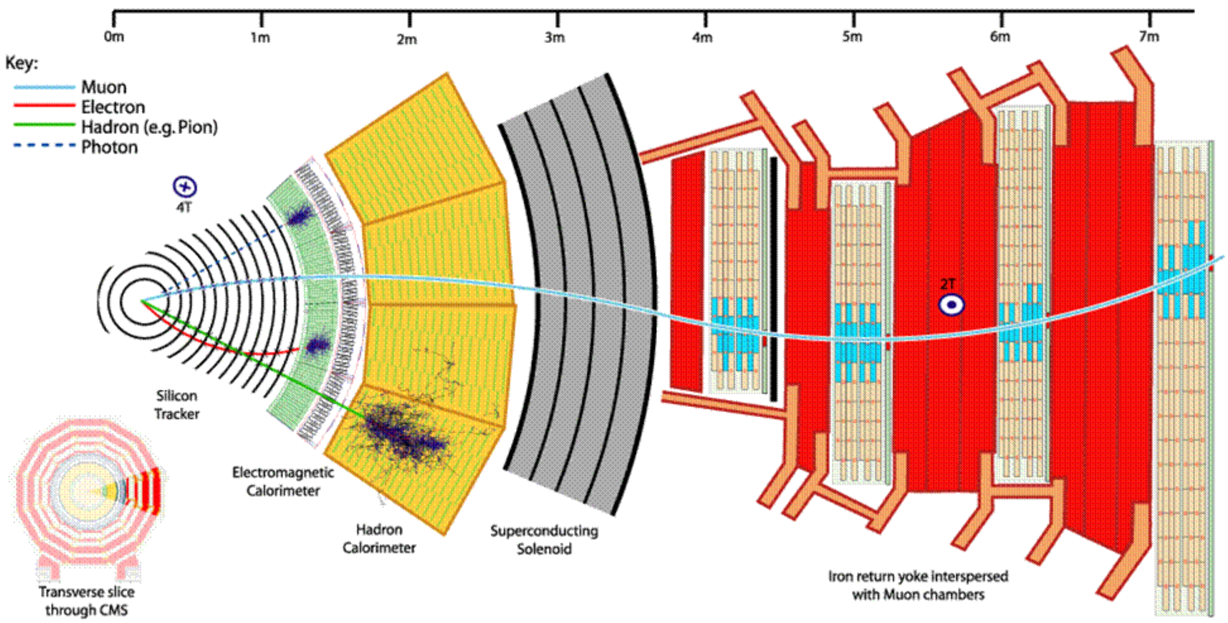

Figure ii – Diagram of particle trajectories through the various components of the CMS detector thanks to CERN's CMS public twiki page.[11]

i. HL-LHC Upgrade

Integrated luminosity is considered a measurement of the collision rate but actually measures the number of particles sent through the collision point in a given time, since not all of these particles will actually collide. Scientists want as high of an integrated luminosity as they can get, as the more collisions there are, the more likely they will see rare processes occur. During Run 2 of the LHC, the integrated luminosity was approximately 140 fb^{-1}. The higher the integrated luminosity, the more collisions will occur, so every few years the LHC is upgraded to increase the luminosity. The most recent upgrade was made for Run 3, where the expected luminosity is about twice that of Run 2. The HL-LHC expects to increase the luminosity by another factor of 10 more than Run 3.[12,13,14]

The HL-LHC will allow for more in-depth analyses of Higgs boson and other particle events and searches of beyond the standard model predictions. The HL-LHC requires plenty of upgrades and new technology to achieve this goal. The magnets outside of the collision points at CMS and ATLAS will be upgraded to help focus the beams to ensure more collisions. There will be upgrades to help protect the lifespan of the equipment with machine protection as well as the lifespan of the beamline itself, as the number of protons in the beamline decreases as collisions occur over time. Not only will there be upgrades to the LHC, but to the CMS and ATLAS detectors themselves. In addition of upgrading the existing detectors, the HL-LHC CMS detector will have a novel MTD installed. The MTD, however, utilizes the advancement of ultra-fast electronics to add a very precise timing to spatial reconstruction.[14,15]

III. MTD

The MTD focuses on the "precision timing of the charged minimized ionizing particles."[15] Currently, the collisions occur approximately 180 picoseconds apart and the MTD aims for a precision of 35 picoseconds. The MTD will have multiple regions, including the central barrel region and the endcaps (Figure iii). Crystal scintillators and silicon photomultipliers (SiPMs) help track the particles in the central barrel region of the detector. The scintillators give off light as particles pass through them which is then recorded by the SiPMs. The endcaps track charged particles by gathering the signals using "Low Gain Silicon Detectors."[15,16]

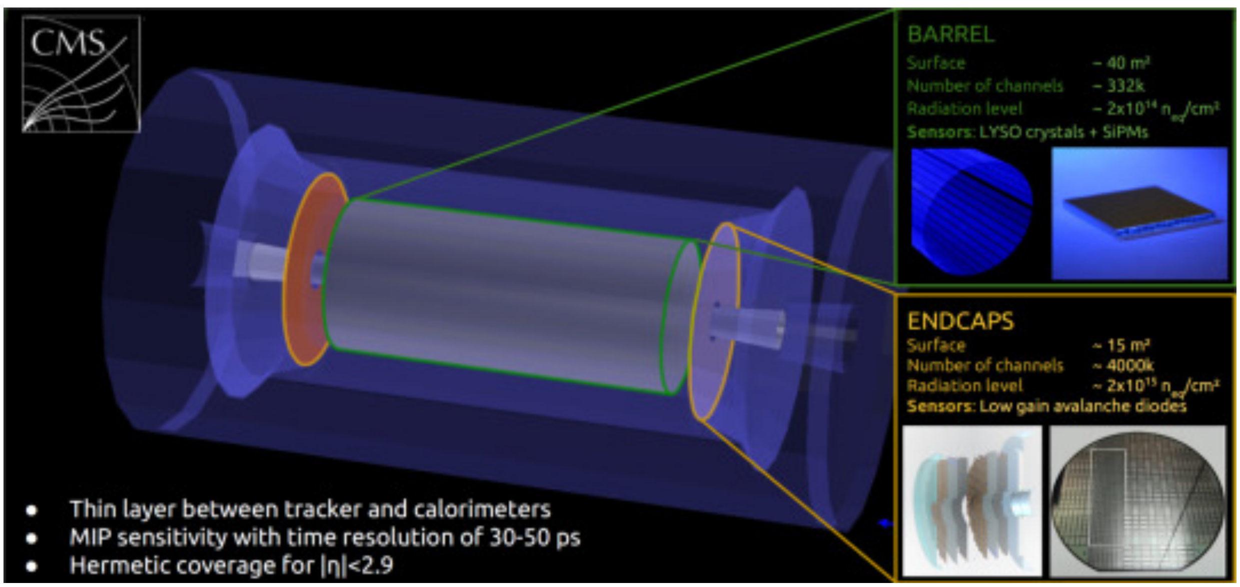

Figure iii – Schematic view of the MTD in the HL-LHC CMS detector thanks to CMS through ScienceDirect.[16]

With the high volume of collisions from the HL-LHC, pileup becomes an issue. Pileup occurs when two bunches of particles collide causing multiple particle collisions almost simultaneously. In each collision of particle bunches, typically only one rare interaction appears, which is what analyses are interested in, but the other common collisions known as pileup interactions are recorded as well. Occasionally, extra particles from the pileup interactions will be mistakenly traced back to the rare collision's vertex, the point at which all the particle trajectories on an event meet, because of the proximity of all the collisions. The detector mitigates the effects of pileup by separating numerous tracks through the precise timing and tracking of particles back to their respective collision vertices. The precise timing for the higher luminosity of the HL-LHC is especially useful as, "Other tracks pointing roughly towards the vertex but coming at the wrong time, can be eliminated from consideration as contributing to that particular collision"[16(p2)]. With this precision timing, the MTD will allow for more collisions and, therefore, more events of rare interactions. Beyond the standard model studies for new phenomena, such as long-lived SUSY particles and higher mass bosons, will be made possible as the MTD will mitigate the effects of pileup from the HL-LHC.[15,16,17,18]

IV. Concentrator Card

Part of the MTD is the barrel timing layer (BTL). The BTL consists of SiPMs that record signals from the light given off by the scintillators as particles pass through them. Precise timing is determined by Time-of-Flight at High Rate (TOFHIR) front end (FE) boards by analyzing this signal. Each TOFHIR FE board holds six TOFHIR application specific integrated circuits (ASICs) chips that determine the amplitude and precision timing of the signals of 32 SiPMs each. The development of TOFHIR ASICs chips was completed through modification of a medical chip used for PET scanning, including upgrading the timing system of the chip.[17,19]

CCs, which will be produced and tested at Kansas State University, will be placed in the BTL of the MTD. The CCs communicate between the ASICs and a data acquisition system, along with powering up and controlling the configuration of the boards. There are four TOFHIR FE boards connected to each CC. The CCs distribute bias voltage and low voltage power to them. CCs link the ASICs with the data acquisition system by sending data and control commands through low power giga-bit transceivers (LpGBTs). The LpGBTs allow for configuration of the FE cards and the accumulation and distribution of data via a VTRX+ optical cable to the ASICs. The control signals are given by giga-bit transceiver – slow control adapters (GBT-SCAs), which also allow for monitoring of the system. An ALDO voltage regulator is also necessary as it provides power regulation for the GBT-SCAs. Finally, clock signals are received by the RAFAEL chips for the timing distribution. As explained, the CC is a complex system with precision timing, with SiPM read outs of the scintillators better than thirty picoseconds. This precise timing is necessary as light travels approximately nine millimeters in those thirty picoseconds and the particles from the interactions will be travelling at similar speeds near the speed of light.[17,19]

The CCs have a production process that consists of three steps, the prototype, pre-production, and production itself. During each stage, the CCs will be tested to make sure they work properly before moving on to the next step in the production process. For testing, each I/O must be tested on the LpGBT, RAFAEL, and GBT-SCA chips. Each chip has multiple different processes to test their components with various scripts communicating with those components for testing. Previously, each script required being called individually by hand in the correct order for a particular test. In order to improve and streamline this process, a GUI was developed to include all functionalities of the various chips in one central software that will allow for multiple CCs to undergo testing at once.[19]

V. Graphical User Interface

The GUI is a working project written in Python 2 that will have additional development in the future. The final interface will include 3 modes: debug, data taking, and commissioning. The debug mode will have low level control of everything on the CC. The data taking mode will have high level control, as well as it will initialize, set inputs, and have front end controls. The commissioning mode will step through all the CC version 2 (CCv2) scenarios, perform automated tests, and read registers to check the return value. Both the data taking and commissioning modes will have clean interfaces without the various tabs in the debug mode.

i. Debug Mode

The debug mode is the most in depth aspect of the GUI. There are several different tabs, each with a specific control of the CC. The scripts tab (Figure iv) includes modified versions of all the original scripts used to control the GBT-SCA chips. On the tab, there are scripts that connect directly to and control their respective GBT-SCA chips. The buttons run these scripts and indicate whether the command worked properly or not by changing from white to green or red, respectively. Along with the IDread, Bread, DIRread, and DATAOUTread buttons, there are output text boxes that give the value for each "read" script. The general purpose input and output (GPIO) scripts (GPIOon, GPIOoff, GPIOset, GPIOclr) all use the GPIO value entry. Each script takes the entered value and completes its command to the GBT-SCA. Also, in each GBT-SCA section there is an error output that gives the user a possible reason a command did not work properly. The final aspect of the scripts tab is the general output text box at the bottom. This text box stores the outputs of every script that gives a command to the GBT-SCA for easier debugging.

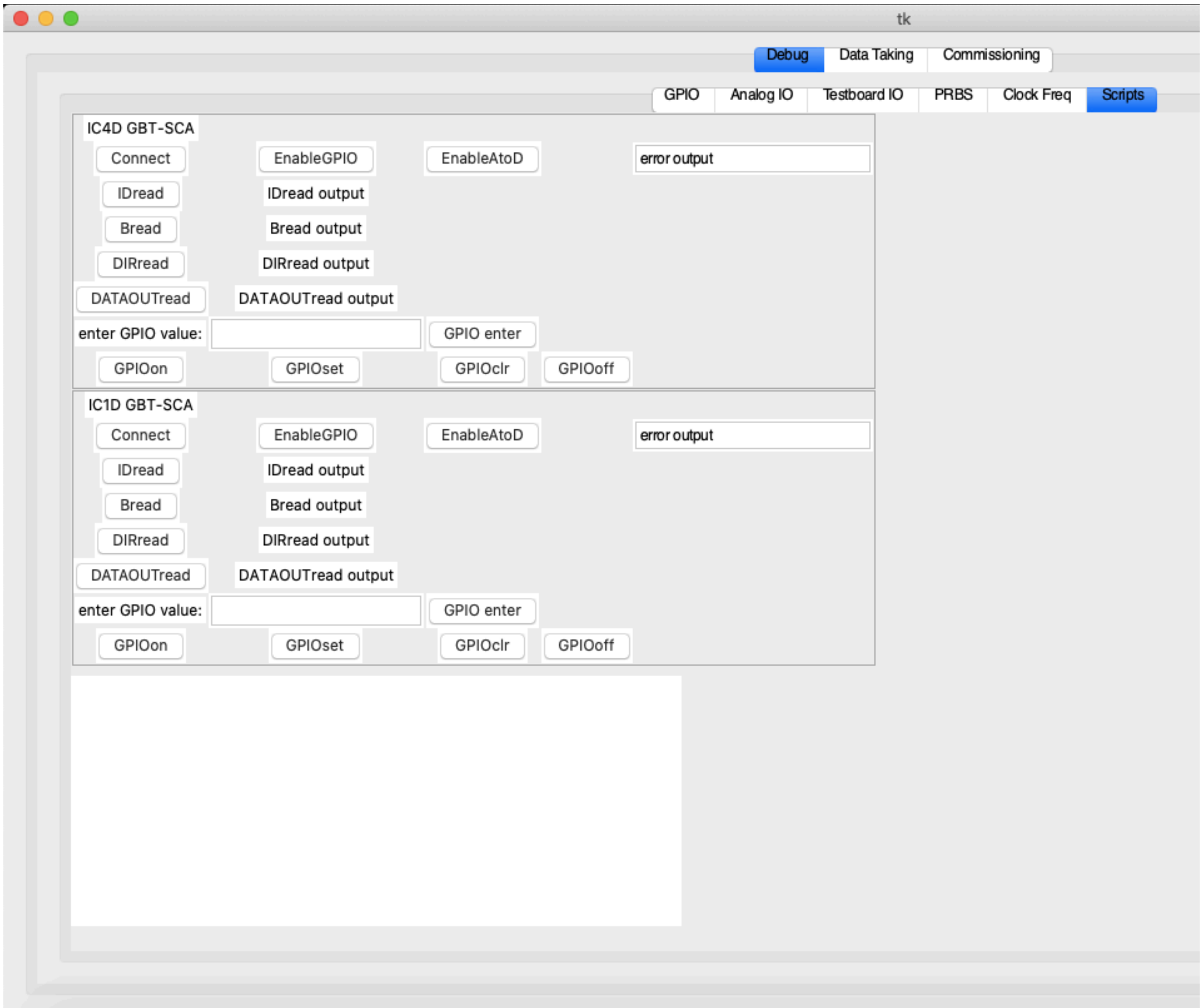

Figure iv – Screenshot of the scripts tab of the GUI

The GPIO tab (Figure v) has buttons that connect to both the GBT-SCA and the LpGBT chips. There are 32 inputs/outputs (I/Os) on a GBT-SCA chip, each with a specific functionality. On the GUI, there is a label and two buttons for all 32 I/Os. The first button is the on/off button. When pressed, the GUI runs the GPIOon or GPIOoff script, depending on the original state of the I/O, then changes the color from white (off state) to green (on state) or red (error) or from green to white or red. The second button is the set/clear button and works in the same manner but runs the GPIOset or GPIOclr script instead. There is also a refresh button at the bottom of the tab that allows the user to open the GUI and have the buttons set to the correct color (state) both on startup and while running.

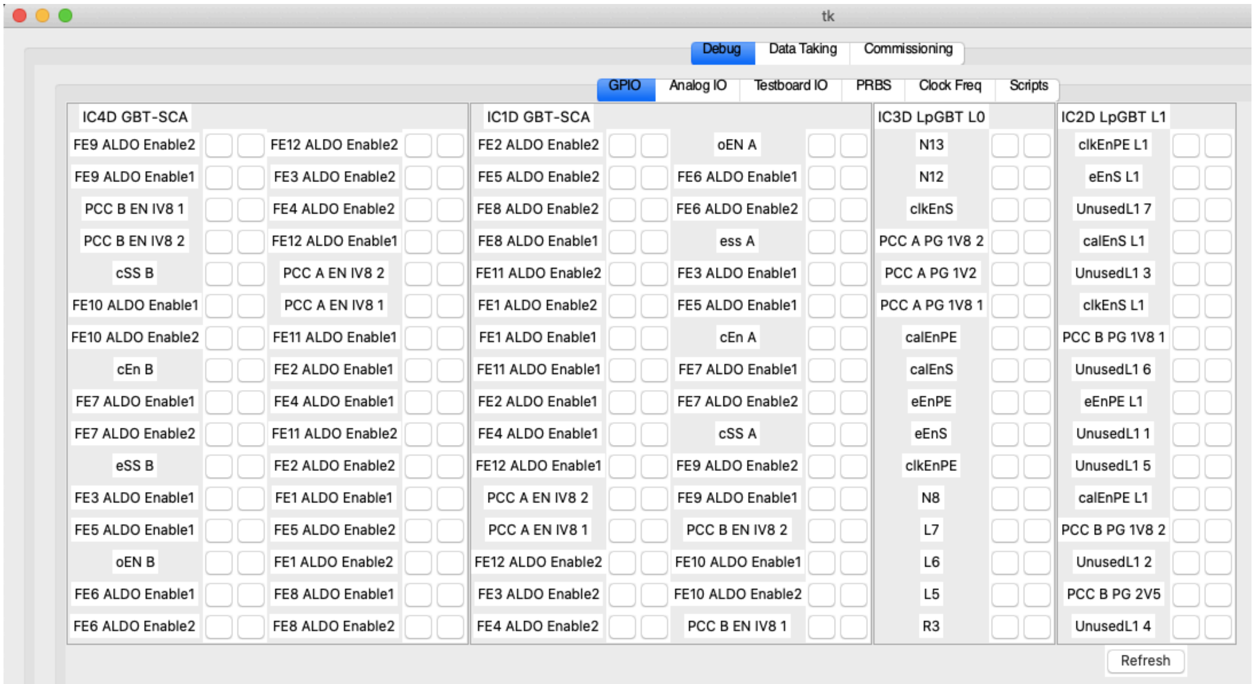

Figure v – Screenshot of the GPIO tab of the GUI

The GPIO tab will also have controls for the LpGBT chips, with a label and two buttons. The LpGBT chips will have a different way of communicating than the GBT-SCA chips. When the GUI sends a command to the LpGBT chips, a separate LpGBT script will be called using Python 3. This separate script will take arguments sent with the command, access a library of operations, and return the status of the LpGBT chip back to the GUI. This formatting was selected to allow the user to choose whether the CC being tested has version 0 (v0) or version 1 (v1) of the LpGBT chips. The GUI will default to using v1, but if the user gives the v0 argument, the v0 map of the library of operations will be uploaded instead. The two buttons for each LpGBT GPIO will have similar uses as the GBT-SCA GPIO buttons. The first will be an on/off button and the second a set/clear button. The buttons on the GPIO tab for the LpGBT chips will turn from white to green or red, again, indicating the status of the command given.

The Analog IO tab (Figure vi) has outputs of measurements for both the GBT-SCA chips and LpGBT chips. For the GBT-SCA chips, there is a label and two outputs. The first output gives the user the measurement in hexadecimal and the second gives a calculated measurement in amps or degrees Celsius. The LpGBT chips only have one output as this connection is still in development, but will most likely move to two outputs, similar to the GBT-SCA chips. There is a refresh button at the bottom of the tab that runs the scripts that acquire the hexadecimal reading, then runs the reading through functions that calculate the actual measurements.

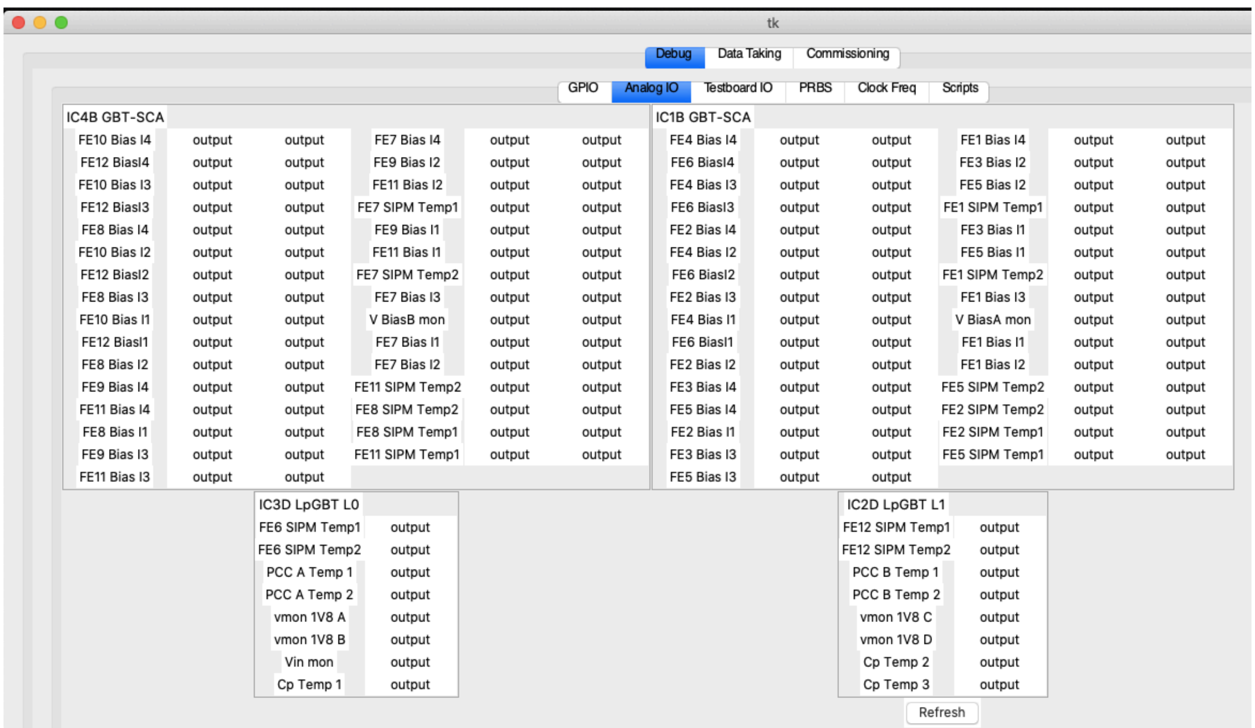

Figure vi – Screenshot of the Analog IO tab of the GUI

The PRBS, Clock Frequency, and Testboard IO tabs are the remaining debugging tabs to be developed. There will be two types of PRBS, one for the testboard and one for the LpGBT chips. This tab will have monitoring of the bit error rate for each PRBS. The Clock Frequency tab will read and check registers, then display results like the Analog IO tab. The Testboard IO tab will also read and check the appropriate registers with a display similar to the Analog IO tab. Each of these tabs will use scripts that are not currently encompassed in the working GUI.

ii. Data Taking Mode

The data taking mode will be a monitoring system of the CC during the beamline testing phase. In this mode, the user will initialize the setup of the CC. This mode will have buttons for different configurations for setup. The GUI will then turn on specific I/Os for the CC and have a monitoring system keeping track of the status of those I/Os, as well as any measurements, such as the Analog IO tab measurements. This mode will also include front end controls, the communication system between the CC and the computers in the detector. During setup of the testboard, one must turn on communications from the CC to the computer, as well as set which links to turn on. The user will be able to set up not only the configuration for the CC, but also turn on this communication system in the data taking mode.

iii. Commissioning Mode

The commissioning mode is where all the automated tests will be completed. This includes stepping through all the various CCv2 scenarios. The idea for these tests is that the GUI will cycle through given functions from the debugging mode. The structure of the debugging mode was created in a manner that would allow for easier development of the commission mode. The developer for the commissioning mode tests will create a function that calls on the functions that they want to run for that test and send the results to a run log on a database. For example, if the user wants to test the GPIO of a GBT-SCA chip, there will be a button to start an automated test.

The test would then call the function for all 32 GPIOs to turn them on, set them, clear them, and turn them off, with confirmation checks in between each stage sent to the run log.

iv. Coding Structure

With so many different functionalities in the GUI, a future developer or user will need to know the structure of the GUI codes. The GUI global script is where the tabs, labels, buttons, etc. are created for use amongst all other scripts. The GUI board test script holds the design of the interface itself. In this script, the different tabs, labels, buttons, etc. are formatted and placed in their respective positions. The GUI button functions script is where the functions called by the buttons are located. There are three aspects to the function script. The first, to make all the generic functions for the Scripts tab. The second, to make the specific functions for the buttons on the GPIO tab. he functions that perform the measurement calculations on the Analog IO tab, including an array of resistances at different temperatures for more accurate temperature calculations.

The GUI button functions scripts calls the SCA functions script, which is where the modified versions of the original GBT-SCA chip scripts are located. The GUI button functions script sends the location of the I/O to be accessed and the GBT-SCA chip number. The SCA functions script takes this information and runs the specified function to communicate with the GBT-SCA chips. This script also calls the GUI getNode functions script. The GUI getNode functions script receives the GBT-SCA number and uses it to grab the correct location of that GBT-SCA chip from the address table for the SCA functions script.

The LpGBT functions scripts is the only Python 3 script and is also called by the GUI button functions script. This script receives the LpGBT chip number and the I/O location and performs all the LpGBT chip communications. The current working version returns whether the LpGBT chip communications were performed correctly or not but will be further developed to return values back as well. There is additional development planned, but the current structure will allow a future developer to add more functionality in a timely manner.

VI. Summary

The CCs for the MTD being built in the HL-LHC upgrade will be assembled and tested at Kansas State University. To improve the testing process, a GUI was developed to test the individual parts of the CCs. The GUI has three working tabs for the debug mode that currently have functions for the GBT-SCA and LpGBT chips. These functions were designed for easy utilization in the commissioning mode development in the future. The GUI has already made testing the CCs easier in the current stage of their production. With further development of the remaining debug mode tabs, the data taking mode, and the commissioning mode, the testing process of the CCs will continue to be improved.

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