

From Test Stand to M-Test: The Detector Design Process

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Abstract

This summer I worked for 12 weeks at Fermilab Test Beam Facility (FTBF) under the supervision of Mandy Rominsky. I was presented with two main tasks for the summer. Firstly, I built and tested a cosmic ray stand with various electronics, instrumentation, and software components. Secondly, I aided in the installation and development of MIDAS, a data acquisition system that will include the monitoring and data records for every aspect of the test beam facility's MTEST beam.

Introduction

The test beam facility at Fermilab allows different group users to come use a characterized particle beam for all detectors tests. The high-energy hadron beams are reserved for research and development of detectors¹². My tasks for the summer aimed to improve the data acquisition system as well as learn the fundamentals of a cosmic ray test stand in order to implement certain pieces into the beam and for data collection. The data acquisition system, MIDAS, allows for the monitoring and control of many devices in the beam. Specifically, I learned about the lead glass calorimeter and about the advantages to applying this detector to the test beam. Every detector has a separate frontend file in order to connect the detector to the data acquisition system and the online database. The system also needs to be monitored for slow controls data, such as high voltage, low voltage, temperature, humidity, and current. To improve MIDAS even more, I was given the task to control the high voltage through a frontend as well.

Additionally, I learned the fundamentals of the cosmic ray test stand. This included knowledge about NIM and CAMAC logic, scintillator detectors, and oscilloscopes. The stand allows for manual data collection as well as digital collection. Further, the oscilloscope allows for the signals to be visualized qualitatively. The cosmic ray test stand used the atmosphere as the beam.

Cosmic Rays

Muons originate from cosmic rays and interact with many particles while traveling through the atmosphere. The interactions of muons are heavily due to ionization only and can travel large distances. They do lose energy in proportion to the matter that they must pass through². Muons are commonly experimented with and researched because these particles are fairly easy to detect with high accuracy and low background interference and close to no interactions³. The particles have decently long lifetimes and allow them to be closely monitored on many levels.

The detection of muons can be attributed to identification through muon parameters of measurement. Identification is based on the comparison of the parameters of the particle and the known values of mass, charge, lifetime, and decay modes. The low rate of interaction results in only minor energy losses and small displacements. A muons lifetime is approximately 2.2msec and, in particle physics, is discussed as a stable particle³. Muon detection is based on the ability of the particle to penetrate thick absorbers with little to no energy losses. The resolution of the detectors is limited by the random scattering and difficulty in tracking the particles. The lost energy of the particle is absorbed by the matter that it is passing through. As there is more matter or a longer distance to travel through, there is more absorption. The cosmic rays that produce the particles also pass through a variety of environments such as the numerous layers of the Earth's atmosphere².

Muon detectors are instruments containing the tracking detectors, an absorber, and the electronic software necessary to read out data. Detectors are classified based on their resolution time and sensitivity to background. The paddles will be scintillation counters as part of the overall coincidence counter. The scintillators are used before and after the absorber in order to identify triggering³. Some issues in detecting muons can be attributed to the background "noise" picked up. To reduce this interference there can multiple detectors to read out more consistent data. By installing shielding pieces the background may be better estimated and taken into account. The location of the detectors can determine the precision based on the alignment and accuracy. The higher radiation that is emitted from muons can become an issue in detection³.

Particle Detection

Various detectors are used for tracking the paths of particles, measuring the energy of the particle, and helping to identify the particle based on its' radiation emission. Tracking detectors are used to expose the paths of particles by recording electrical signals triggered by the particle moving through the device. This is especially useful for highly charged particles but less effective with muon particles due to their lack of interaction with matter, unless the matter is plentiful and very dense. The detector tracks the path of the particle and can be reconstructed into visible pathways on a computer⁴.

Calorimeters are devices used to measure a particle's energy loss as it passes through a material with known characteristics. The calorimetry detector is intended to absorb most of the particle's energy deposited within the device. Calorimeters have both "passive" and "active" material layers where the passive material is high density and highly absorbing and the active medium is where the energy is deposited. While there are many types of calorimeters that function well for electrons, photons, protons, and neutrons, muon and neutrino particles do not interact with this detector and cannot be stopped in the passive material.⁴

Further particle identification processes can be based on detecting radiation emitted by charged particles. One method works because when a charged particle travels faster than light does through a given medium, it emits Cherenkov radiation at an angle that depends on its velocity. The particle's velocity can be calculated from this angle. Velocity can then be combined with a measure of the particle's momentum to determine its mass, and therefore its identity. The second method is related to the energy phenomenon of a particle and is accomplished by passing a fast, charged particle across two electrical insulators with various resistances to electric currents, causing the particle to emit transition radiation. This is a final step to identifying a particle and is used to verify results or recognize disputes to current theories.⁴

Particle-identification can be accomplished by scintillation detectors, Time-of-Flight methods, or Cherenkov detector. Scintillators are one of the oldest types of radiation detector but have vastly improved in efficiency and detection. The purpose of scintillators have not changed over the years and aim to produce large light outputs in a visible range. The light output can be converted to voltage pulses in order to be processed and recorded. The electrical signal formed from the scintillation light is converted by photomultiplier tubes.⁴

Particle detection uses many resources to classify and identify various particles. High energy physics has progressed exponentially in the past ~60 years largely due to particle detectors and identifiers. The confidence in these techniques and verification of the Standard Model is attributed to these detection devices.

Test Stand

Using cosmic ray showers is a great resource in order to test detectors, hardware, and software in a lab setting. The test stand in the Fermilab Test Beam Facility (FTBF) has crates for NIM and CAMAC logic as well as a high voltage power supply.

NIM Logic

Nuclear Instrumentation Module standard defines mechanical and electrical specifications for electronics modules used in experimental physics. Using modules in electronic system is advantageous because it allows flexibility with the interchange of instruments as well as the maintenance required by the instruments. In a NIM logic crate, there is room for twelve modules, which shows the potential for a complicated system if necessary. The modules run independently and are not connected through the crate backplane⁸. Therefore, NIM is well suited for logic modules that do not require digital data communication, such as discriminators, pulse generators, and amplifiers.⁹

A discriminator has an output voltage when the amplitude of input pulses exceeds a predetermined value. The PMT signal is converted to NIM logic which can be read by instruments such as an oscilloscope, in order to visualize the signal. Between the discriminator and oscilloscope, a logic gate module can be used as a coincidence counter. The logic gate reads “and” signals as in coincidence between two or more PMT signals. The coincidence can also be visual on the oscilloscope and read out in a scaler module.¹⁰

Scintillators

Scintillators can be made of various materials that each have certain advantages. Solid plastic scintillators are particularly useful for gamma ray counts with energies above 100 KeV and used for detection of charged particles. They are cost effective and have the ability to be made in virtually any size which becomes helpful in large detection areas that require increased sensitivity.⁷

Liquid scintillators, used mainly for alpha and beta particle detection, are more efficient in counting. The contact between the active material and liquid scintillator is very close to allow for higher efficiencies, up to 100% for phosphorus-32 scintillation.⁷

Fiber optic scintillators are highly useful for tracking detectors, real-time imaging systems, and neutron imaging. Fluorescent dopants in the core of the scintillators produce optical and radiation characteristics but at the expense of the light reduction length. These scintillators generally have high yield efficiency but low trapping efficiency.⁷

Properties of a good scintillator detectors include low gamma output, high efficiency of converting incident radiation to photons, light tightness, transparency to its own scintillation light for better light collection, and short decay time, to accommodate for high event rates. There is a large focus on the process to become light tight because it significantly affects the efficiency of the scintillator.⁷

Photomultiplier Tubes

Photomultiplier tubes (PMTs) are useful for light detection of very weak signals. After the absorption of a photon (produced in the scintillator), there is an emission of an electron which can then be amplified by the photocathode. PMTs can produce a signal even in the absence of light from the thermal emission of electrons in the photocathode and stray high-energy radiation. While there is other electronic noise that can also affect the efficiency of the PMTs, there are ways to filter the noise and confirm events. The photomultiplier tubes at FTBF are each specifically characterized based on optimal high voltage. They have been tested and verified to work at certain conditions.⁸

Set-up

To understand the fundamentals of the stand and detectors, there is a basic approach to visualizing an event. The high voltage power supply provides a current to the PMT and scintillator which then creates a signal through the cable connected to the NIM logic crate. The signal can be visualized through connection to an oscilloscope at proper gate width, timing interval, and amplitude.

Coincidence Counting

One way to confirm signals from cosmic rays is to implement a coincidence counter. The data collected from one scintillator is not certain enough to accept as the standard for an experiment. By placing two scintillators in close proximity and parallel to one another, the results can be confirmed in order to verify the event. The coincidence can be seen as a signal on the oscilloscope or as a scalar quantity in a scalar NIM module.

CAMAC

Computer-aided measurement and control logic requires digital data communication among the modules in the crate. This juxtaposes that of NIM logic and the CAMAC logic also has the digital data bus to provide a communication between the modules and a computer. Another major difference between the two logic systems is that CAMAC crates have thinner module slots which enhances the amount of the electronics which can be used in a system.

Data Acquisition

When introducing the CAMAC system into the test stand, the data acquisition was expedited and able to be graphed in a way that visually represented the events through the scintillators as well as the energy loss in the calorimeter. The addition of a fan-in/fan-out NIM module defines the number of digital inputs that an output of a single logic gate can feed.

The CAMAC crate fits 25 single-slot modules. For the particular set-up of the test stand, the modules used had one gate input as well as 12 ADC inputs resulting in a data file with 13 columns of data. The data is analyzed with Root through the use of histograms. The histogram groups the data columns into bins of unfiltered values which are assigned energy values after the calibration of the instrumentation.

Lead Glass Calorimeter

Calorimeters generally consist of “passive” and “active” material layers. FTBF has a lead glass calorimeter, which has a cost advantage and is easy to handle. For these reasons, this type of calorimeter has been widely used for high-energy physics applications. The passive material is the lead because it is high density and absorbing.¹¹

Calibration

Each detector functions differently but can be calibrated with known sources. Cosmic rays can be used in this process as well, in order for the lead glass calorimeter to operate optimally. By placing the detector in the test stand in a parallel system with two scintillators above, and one below, and recording data, the resulting graph will show a pedestal, due to electronic noise, as well as the deposited energy, and can therefore calculate the calibration constant. The additional third scintillator placed below the lead glass in the system will assist in tracking the particles' potential path by showing which particles pass directly through the calorimeter and deposit energy instead of the particle showers that may hit at an angle.

Further calibration takes place by rearranging the system so that the lead glass calorimeter is no longer vertical. While recalibrating the detector, the ratio of calibration constant should be directly related to the ratio between the length and side width of the detector. This is due to the fact that energy loss is proportional to the length of material it passes through. The calorimeter at FTBF has been calibrated by not to precision. While the ratio of calibration constants should be ~ 3 , the experimental value is ~ 4 and therefore leaves more room for precision improvements. The next step will include testing the same system at various angles to include more data and increase the significance of the result. This calorimeter could potentially be used in the beam line for various experiments once properly documented.

Implementing the Lead Glass into the Test Beam

The Fermilab Test Beam works to fully characterize all of the facility's instrumentation and data acquisition (DAQ) procedures. The lead glass calibration will increase the available resources for the beam's users. While the initial goal of determining the energy of the particles passing through and depositing their energy into the calorimeter is very useful, an improvement would include creating a frontend file to acquire and record the data in the MIDAS DAQ.

MIDAS

Midas, or the Maximum Integrated Data Acquisition System, is a useful data acquisition system for the test beam because of its versatility. It can function with many features through one program. Two frontends in particular are the CC-USB, and therefore everything connected CAMAC, and the MWPC, for the wire chambers. Each detector has its own frontend code associated with it, and the frontend files are all connected through the master frontend. The master frontend is activated by a trigger and feeds into the event builder. The event builder allows for offline analysis and also records the data. While slow controls are not a part of data collection, they can also be monitored continuously.

Installation

The data acquisition system, Midas, which is a Triumf development, supports many types of hardware. It has the ability to manage a complicated system and the installation process had many complications as well. The installation occurred on a Linux computer.

Slow Controls

Slow controls are one aspect of Midas acting as a monitoring system. The high voltage slow control in particular is controlled by Droege Technology. The Droege voltage monitoring instrumentation is a module for the NIM crate and be read out through an ADC connection to the CAMAC and connect to the CC-USB frontend. There is an additional installation step for the slow controls and an edited frontend. After the high voltage has been successfully implemented into the system, the same process can be used for temperature and humidity monitoring. This is all important to the most optimal functioning of the beam system set-up.

Conclusions

The beam shut-off occurred at the end of July so the current stage of the detector design process is feedback and improvement. My personal reflection of the summer was that I learned so much more this summer than I could have ever hoped for and I couldn't have asked to work with a better staff than at the test beam site.

Results

The results of this summer can qualitatively described as progress. While the calibration of the calorimeter is not complete, we are within a standard deviation that is acceptable. The resolution of the current calorimeter in the test beam is 3% and that is the continuous goal that the facility is working towards for other instrumentation.

Future work

The future work at the test beam consists of continuing to build Midas. There will be additional slow controls added to the system to monitor temperature and humidity. This can be done simply with supplementary edited frontend files. This addition will continue to improve the function of the system as a whole.

Characterizing the system will allow the extension to be made for other particle detectors. Once the calibrated calorimeter is ready to be implemented in the beam, the same calibration process can be used for a Cherenkov detector, Time of Flight system, etc. This instrumentation will be very practical for users and will confirm what is already known about the beam.

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