Time-Of-Flight Trigger Board at CDF[§]

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ABSTRACT

A Time-Of-Flight detector (TOF) was implemented into the Collider Detector at Fermilab (CDF) experiment in order to provide particle identification. TOF consists of scintillator Bars, Photo Multipliers (PMT), and ADC/Memory (ADMEN) that convert digitally charged of pulses from both sides of TOF scintillator Bars and the Time-Of-Flight Trigger Board (TOTRIB). TOTRIB reports coincidences from the east and west side of the detector, helping filter unwanted information that comes from the collision and the photo multipliers. The resulting hits will be analyzed and classified to determine the particles. TOTRIB was designed and built by using Orcad software. The construction of TOTRIB was divided in three stages. Creation, implementation, and verification for function ability of the desire programmable logic are completed in the first stage. The second stage dealt with the drawing and identification of the components that will be used on the board. In the third stage, the components were translated into a readable format to be laid out in the board and connected together. The resulting drawing was then sent to a company for production.

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1. **INTRODUCTION**

Due to large-scale experiments, particle physics has made great steps during the last few decades. Experiments like accelerators and colliders that create high-energy collisions, in which particles are produced, have identified the fundamental forces and mapped the fundamental particles. Physicists need more than accelerators in order to "see" high-energy collisions; therefore, scientists have designed and built particle detectors, huge "cameras" that can take more than a million "snapshots" of particle collisions every second. These detectors can count particles, identify their tracks, measure their energy, record their time of flight, and distinguish one particle from another.

The Time-Of-Flight System (TOF) will perform particle identification by recording the difference between the time particles are detected and the time of collision. Particle collisions produce a great deal of data that is not used to analyze and classify; therefore, we need a mechanism that will filter the most important information such as coincidences and minimum ionizing particle hits. My involvement is to design and build the Time-Of-Flight Trigger Board (TOTRIB) that will help solve this problem. The board will take hits from the east side of the detector as well as the west side and it is going to check for coincidences of hits, sending the resulting particles to the Muon Matchbox for connection with the CDF trigger system to be studied and classified.

2. STUDYING THE INVISIBLE

2.1 Standard Model

The universe is formed from a huge diversity of materials. Different kinds of matter were common in the early stages of the universe; however, this wide variety of matter is composed of a few simple building blocks. All matter that we know in the universe is made from a hundred different types of atoms, each of which is formed by electrons with a negative electric charge circulating a nucleus formed by a proton with a positive electric charge and a neutron. Therefore, the entire universe is made-up of three particles: the electron, the proton, and the neutron [1].

The electron appears to have no internal structure; however, the nucleons (proton and neutron) are formed of some other particles, the quarks. Each proton and neutron is made-up of three quarks; only two types of quarks, called "up" and "down", are needed to build the nucleons. Another particle, the electron-neutrino, is also found in this standard model of matter. Electron-neutrino behaves like an electron, but it does not have charge; it is involved in reactions that convert neutrons to protons and vice versa. Studies of cosmic radiation have revealed that particles created from collisions between high-energy atomic nuclei (like protons) from out of space and atoms at the earth's atmosphere are not just electrons, protons, and neutrons, but some new particles [1]. Particle physicists have found that the fundamental structure and behavior of matter can be described within a framework called the **Standard Model** [2] (See Table I).

TABLE I. Standard Model

QUARKS	**Up**	**Charm**	**Top**
	Down	**Strange**	**Bottom**
LEPTONS	**Electron**	**Muon**	**Tau**
electron-neutrino	**Muon-neutrino**	**Tau-neutrino**	

2.2 Particle Accelerators

Cosmic ray collisions provide a new variety of particles to study, but are very difficult to work with.   To study these collisions in a more controlled manner, high-energy scientists have designed particle accelerators. There are various types of accelerators. In linear accelerators, particles follow a straight path within different regions of electric field, increasing energy as they move. In circular accelerators (cyclotrons and synchrotrons), particles are kept "on track" and guided by magnetic fields following a circular path. Unlike particles in linear accelerators, particles in circular accelerators pass through the same electric field many times [2].

2.3 Detectors

There are two types of collision experiments: smashing accelerated particles into a fixed target and colliding two high-energy particle beams. In the first case, the resulting particles move forward; therefore, the detector is just a cone that will hold the particles. For the second type of experiment, the produced particles may travel out in all directions; thus, the detector must be built to record all the "events" over the full sphere around the collision point. In such experiments a particle detector is used to record as accurately as possible the properties of particles that are produced in collisions. The detector reconstructs each event by measuring the momentum, energy, and trajectory of the particle. From these observations, we can determine the electric charge and mass of the particle and therefore its type. Fig. 1 shows the cross-section of basic components for the detector used for the second type of collision [1].

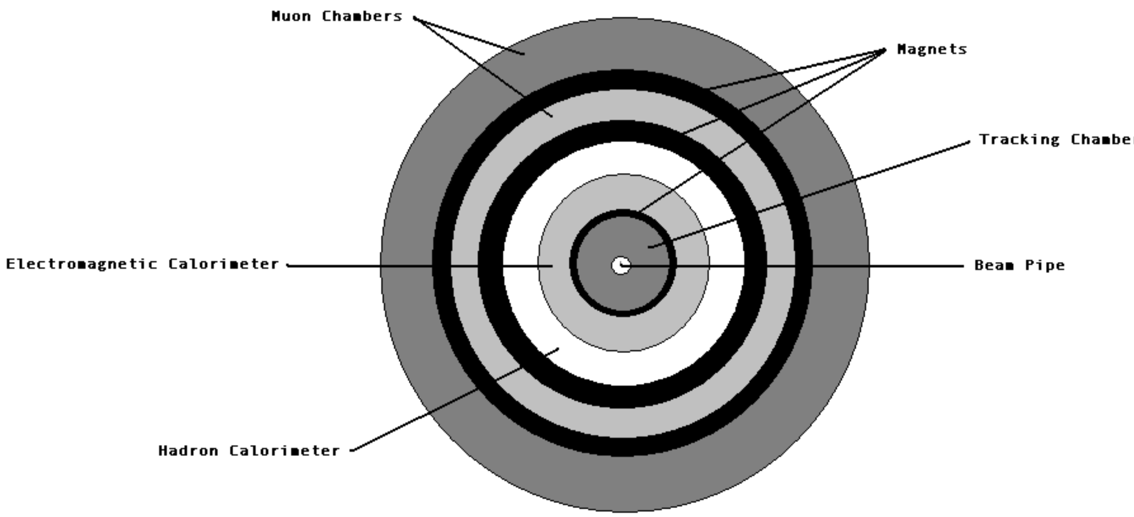

FIGURE 1. Cross-section of detector for collision of two particle beams.

3. COLLIDER DETECTOR AT FERMILAB (CDF)

CDF is a detector experiment at Fermilab; it jointly works with the ***Tevatron,*** which is the world's most powerful particle accelerator. The Tevatron accelerates protons and antiprotons that are close to the speed of light, and then makes them collide head-on inside the CDF detector. The job of the CDF is to study the results of these collisions and figure out the particles of matter and their forces. One of the ways that CDF plans to find and study these particles is by finding their time-of-flight. Fig. 2 shows the cross-section of CDF.

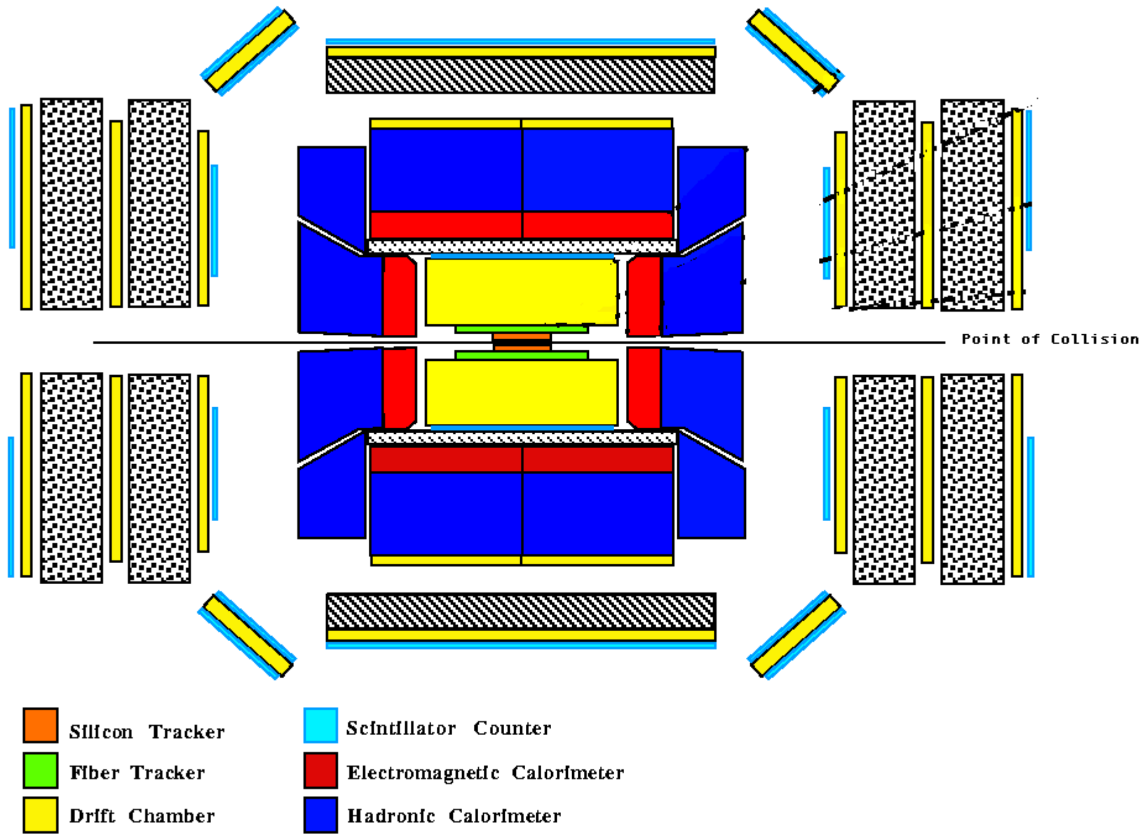

FIGURE 2. Cross-section of CDF

4. THE TOF SYSTEM AT CDF

The TOF system will play a crucial role in determining and classifying particles. The system will measure the difference (time of flight) between the time of arrival of the particle at the detector and the collision time (t_0). The TOF system consists of 216 bars of Bicron scintillator. The bar dimensions are 279 cm x 4 cm x 4 cm, and each bar is installed at a radius of about 138 cm from the beam. Each end of the scintillator bars is attached to a Photomultiplier (PMT). There are 432 PMTs in the entire TOF system. Connected to the photomultipliers are the TOF transition and ADC/Memory (ADMEM) boards that measure the time and charge of pulses from both sides of TOF scintillator bars. The ADMEN boards send the information to the Time-Of-Flight Trigger Board (TOTRIB). The TOTRIB then reports coincidences from the east and west side of the detector and sends the resulting particles to the Muon Matchbox for connection with the CDF trigger system to be studied and classified [3]. Fig. 3 shows the schematic representation of the TOF system.

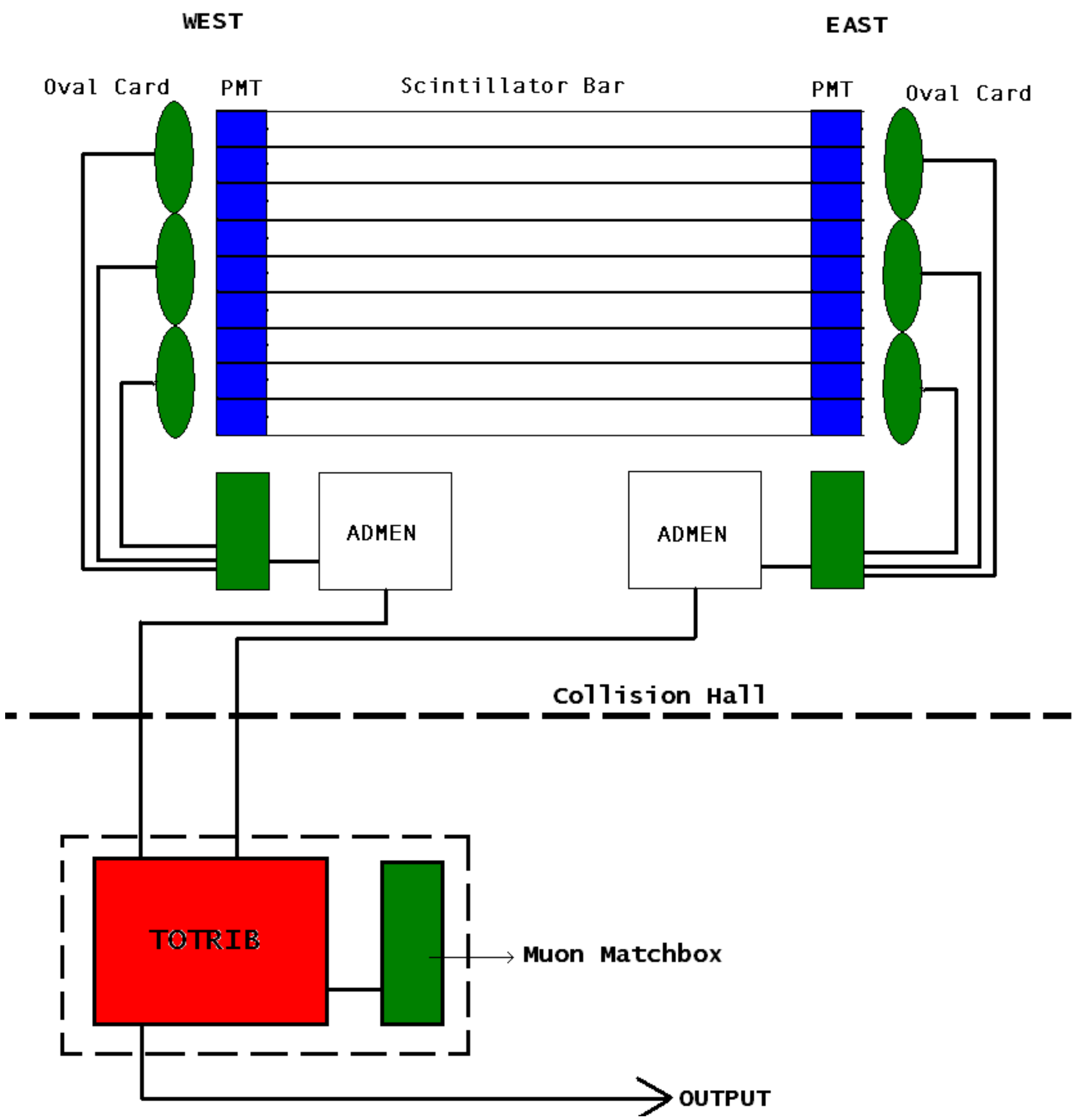

FIGURE 3. Schematic of TOF System

One of the ways to distinguish and classify particles is by their masses. They cannot be easily determined directly; therefore, some other properties of the particles that are related with their masses have to be found. We can find and record the time particles take from the moment of collision to the moment they are detected, time of flight t. Having t and the distance particles travel (d), which is measured by the tracking system, we are able to determine the velocity v:

$$d=vt \tag{1}$$

Momentum of the particles after they collide can be found by the relation:

$$p=q*B*r \tag{2}$$

where q is electron mass, B is the magnetic field of the detector that is applied to bend the paths of the particles after they collide, and r is the radius of the detector. Having v by Eq. (1) and p by Eq. (2), we can use the following equation to find the masses of the particles:

$$p=\gamma mv \tag{3}$$

5. DESIGNING AND BUILDING THE TOTRIB

5.1 Programming the Logic

The TOTRIB receives Low Voltage Differential signal (LVDS) trigger bits from the ADMENs and outputs the coincidences from the east and west sides of the detector. A single TOTRIB will cover 6 ADMEMS on each side, 54 bars, or 90^{o} of the detector. In total, 4 TOTRIBS will cover the entire CDF detector. The TOTRIB has three programmable gates (FPGA) chips, designed to hold the programmable digital logic used to find and count the coincidences. ***Foundation**** is the software used to create and implement the programmable logic to the FPGAs. Fig. 4 shows TOTRIB in TOF environment.

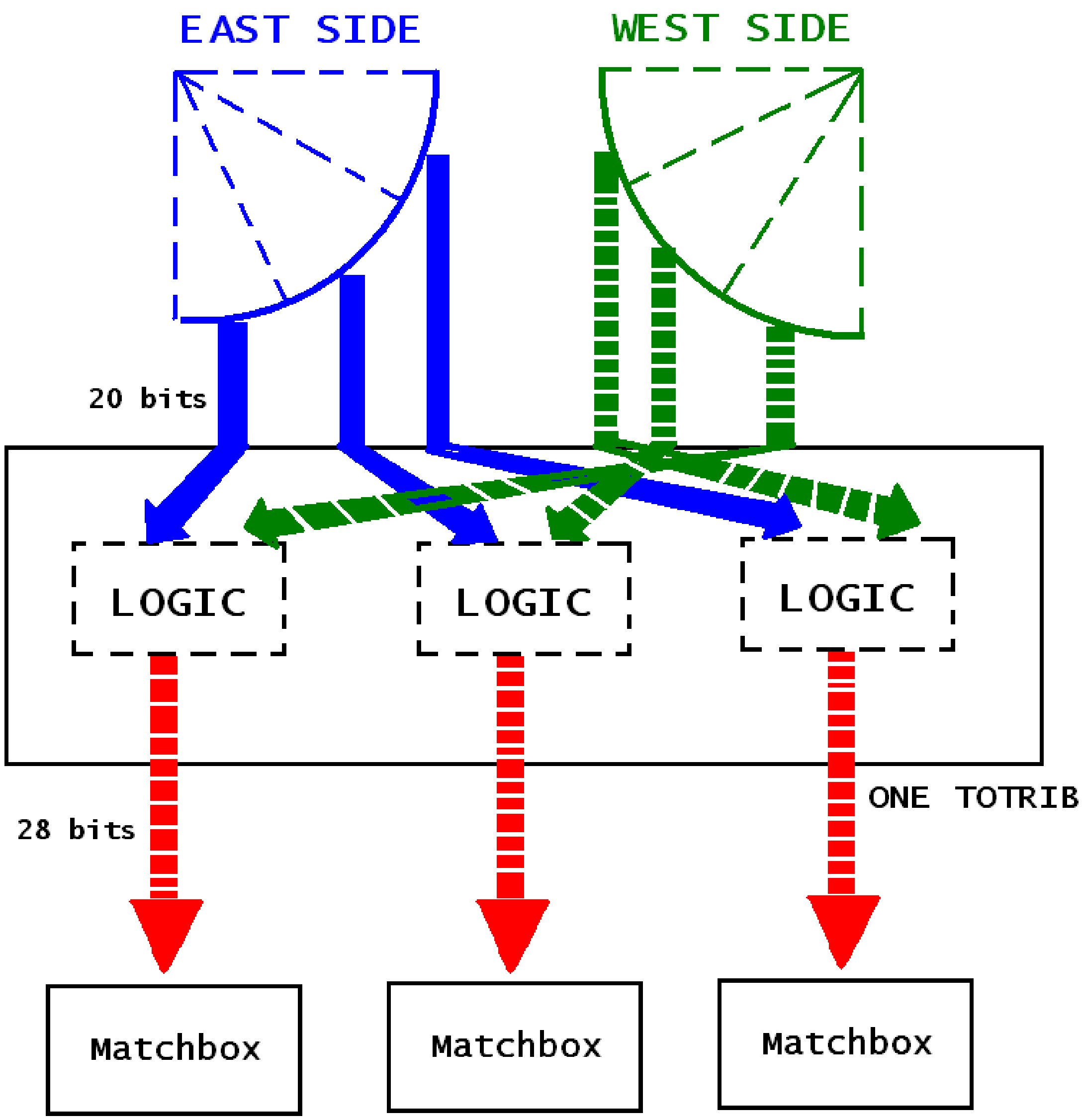

FIGURE 4. One TOTRIB in TOF environment.

Each FPGA has one input connector that receives 40 bits of data from east and west (20 each), a total of 120 bits for a single TOTRIB. The programmable logic divides the data in four main inputs: E0 and E1 for east and W0 and W1 for west. Each input

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* Xilinx Foundation Series, copyright 1985-2000 Aldec Inc.

receives 10 bits and send them to the TOTRIB logic box which checks for coincidences of Highly Ionizing Particle (HIP) and Minimum Ionizing Particle (MIP). The logic has 2 additional input gates (S0 and S1) and two output gates (CM and CMT). The logic outputs a total of 28 bits, which are sent to the output boxes. Names of the output boxes and distribution of data have been previously chosen by CDF. Each input and output has a clock, which controls and times the data coming in and coming out.

Even though all FPGAs of the TOTRIB use the same programmable logic, the function of the additional input and output gates, S0, S1, and W0, W1 respectively, will change. In the peripheral FPGAs, S0 and S1 are grounded because they do not have any use, but in the middle FPGA, S0 and S1 are used to input the resulting coincidences from the peripheral FPGAs. CM and CMT output gates are used in the peripheral FPGAs to output their resulting coincidences and send them to the middle FPGA. In the middle FPGA, CM and CMT are used to output the sum of all coincidences (peripheral and middle).

TOTRIB Logic Box

The TOTRIB Logic Box is the main component of the programmable logic. Its function is to receive the input signals from the input gates, produce the logic that finds and counts coincidences, and output the results to the output gates. VHDL is the software used to create the desired logic of the TOTRIB Logic Box. Fig. 5 shows a complete schematic of TOTRIB's programmable logic.

The final process of creating the programmable logic is to verify its timing. Using the logic Simulator of Orcad, I determine if all the input and output gates are working properly. In order to do this, I write a script file that includes all the gates and their clocks, which are used to send the input data at the correct time. The TOTRIB's total processing time is less than a few 132 ns clock cycles; this time of frame will ensure that TOF trigger information arrives in time.

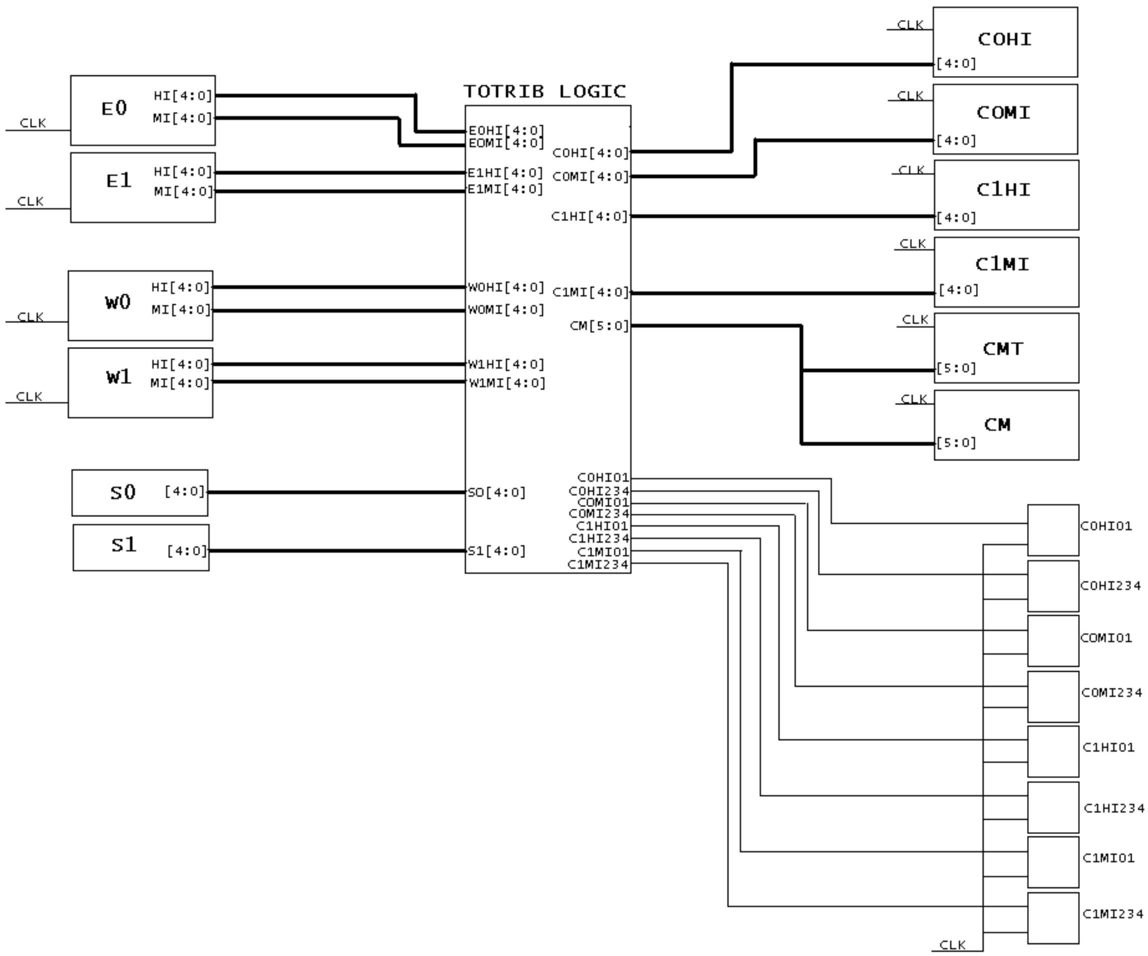

FIGURE 5. Schematic of Programmable Logic

5.2 Creating Components

After the programmable logic is completed and the timing is verified, I draw a schematic representation of the components and their connections with ***Orcad Capture**** program. The schematic contains three main boxes; they are identical and each one has one FPGA and one set of input connectors.

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* OrCAD Program, copyright 1985-1999 OrCAD Inc.

Each FPGA has a set of input and output pins for east and west data. Input pins receive data from the input connectors and output pins send out the resulting coincidences, separately from the others FPGAs, to the output connectors. The middle FPGA takes the resulting coincidences from the peripheral FPGAs through the *S0* and *S1* input pins, adds them together, including its own, and outputs them to the *CM* and *CMT* output pins. The *CM* and *CMT* pins are connected to the digital converter; this device converts the resulting coincidence into readable signals and sends them to the output connectors.

Since FPGA loses its memory every time the power is turned off, it is connected to a memory chip that returns the information when the power restored. Four pins of the FPGA assemble the connection with the memory: *INT*, *CCLK*, *PROGRAM*, and *DONE.* Some other pins like *VDIN* and *VDOUT* are use to send the resulting coincidences to the back plane. FPGAs are powered by 3.3 and 1.8 volts; therefore, capacitors are placed for each input power. The board also has two power converters; these converters transform 5 V supplies into 3.3 and 1.8 V. The FPGAs are connected to another chip that is also of type FPGA. This chip receives four signals that are used to debug, read, and write information, CDF_CLK, CDF_B0, CDF_RECOVER, and CDF_HALT. Fig. 6 shows the three main boxes, which contain the FPGAs and the input connectors. Fig. 7 depicts the FPGA with its input connector. Fig. 8 shows memory chip with its configuration pins. Fig. 9 depicts the digital converter and the connector that outputs the resulting sum of all coincidences. The voltage converters and the connectors for the output coincidences of each FPGA are shown in Fig.10. Fig. 11 shows the chip used to debug, read, and write with its outputs.

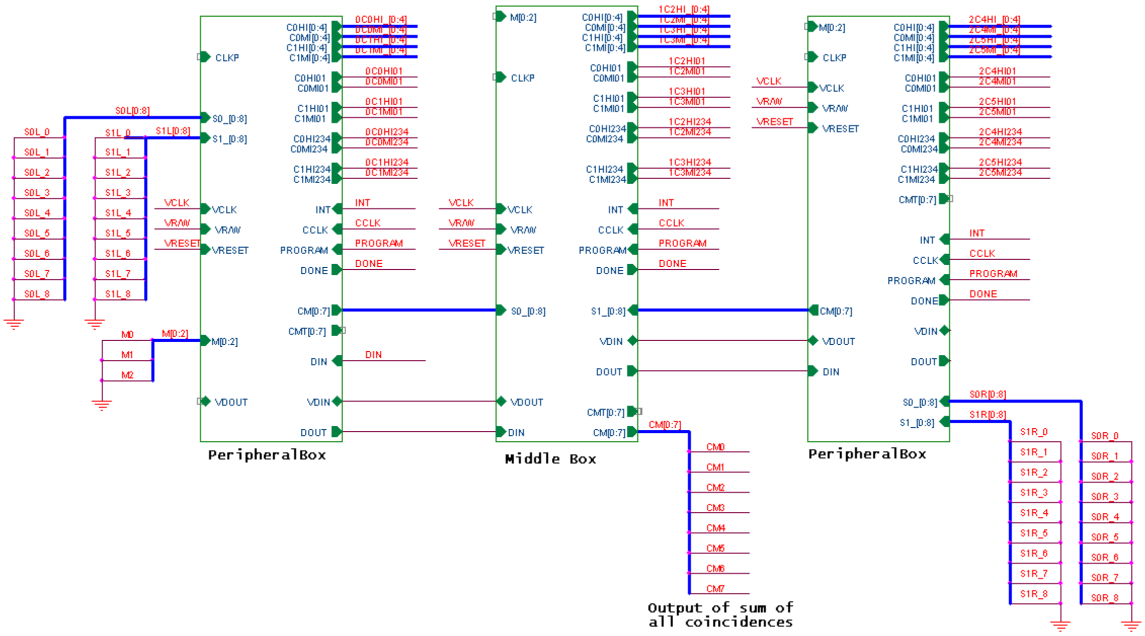

FIGURE 6. Three main Boxes connected together.

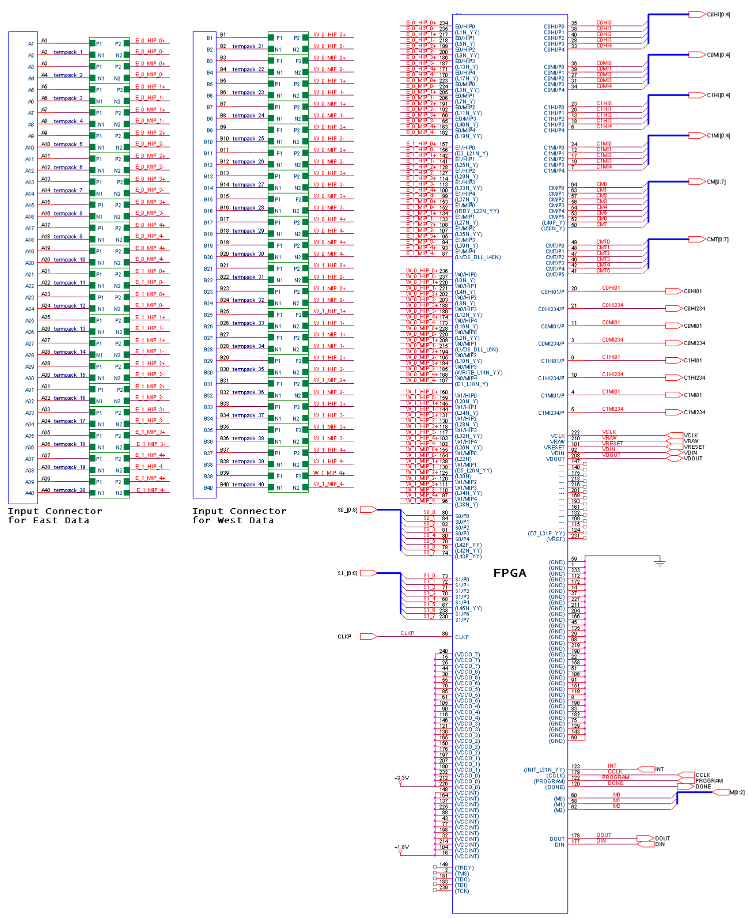

FIGURE 7. FPGA with Input connector.

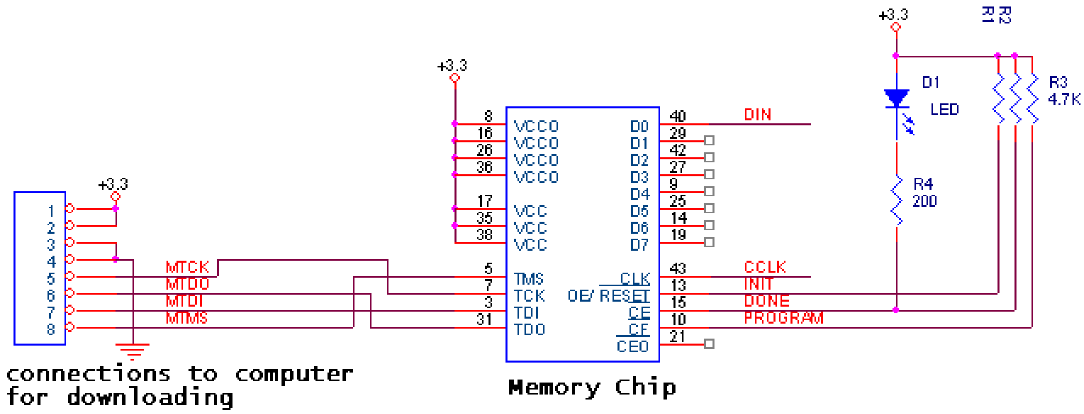

FIGURE 8. Memory Chip.

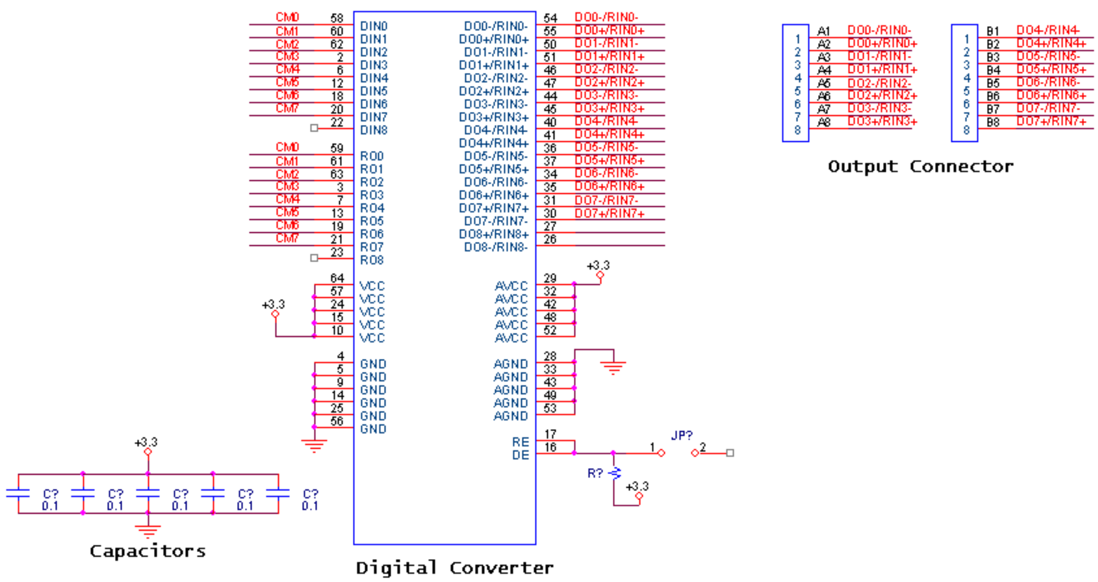

FIGURE 9. Digital Converter and Output Connector.

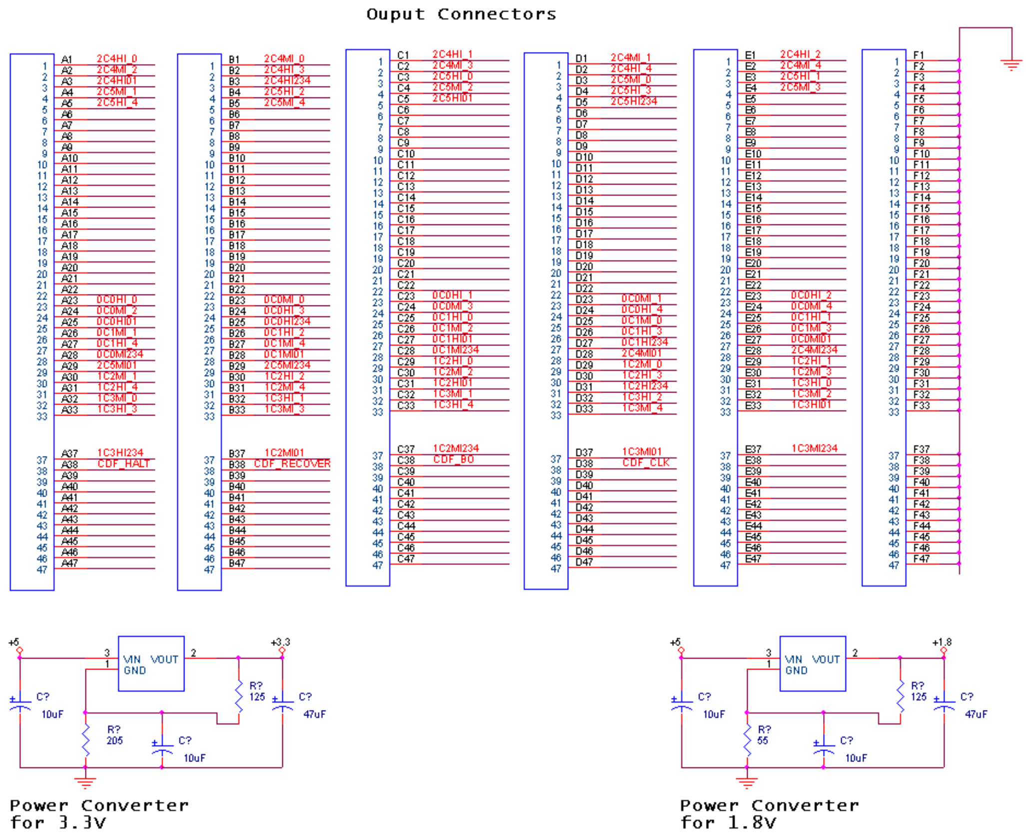

FIGURE 10. Voltage Converters and Output Connectors

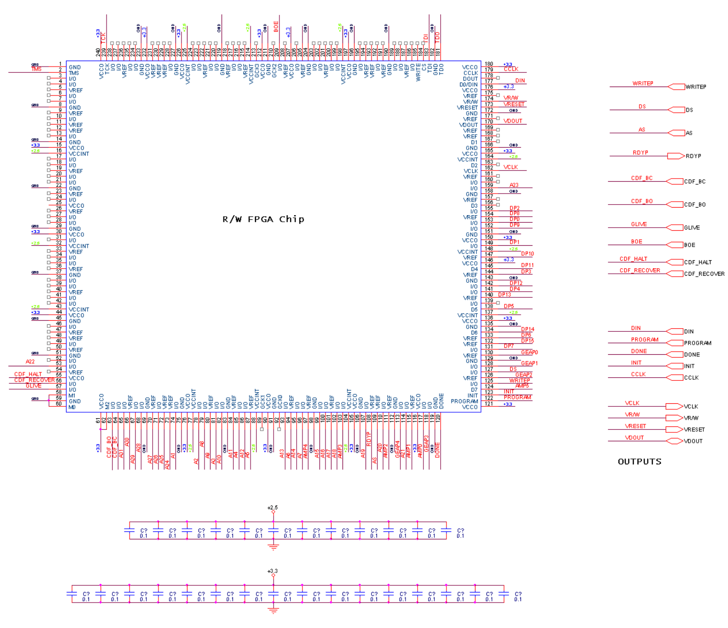

FIGURE 11. R/W Chip.

5.3 Laying Out and Connecting Components

After I completed drawing all the components of TOTRIB, ***Orcad Schematic Editor****[*] implemented their names to standard footprints, compiled them into readable format, and created a net-list that was sent to ***Orcad Layout Plus***[*]. Schematic drawings of the components were translated into real footprints of components, and connections between them became wires that were free for routing. When I finished routing all the components and creating the ground and the power layers, the TOTRIB was ready for production.

The final stage is to take a hard copy of the entire layout of TOTRIB and send it to a company to be produced. After the board is physically created, all the parts are assembled and soldered to it.

6. CONCLUSION

In summary, particle physics has developed significantly in the last decade; this is due to the high magnitude of experiments. These experiments have unveiled a great deal of information about the identity and properties of particles that make up the universe and the forces carried between them. The CDF jointly with The Tevatron are pioneers in these discoveries. Since there is much more to be discovered, in the last few years CDF has been substantially upgraded for data collection and classification. TOF has been implemented to CDF for particle identification using time of flight of particles after collision. TOTRIB will help filter unnecessary data from these collisions, count

[*] OrCAD Program, copyright 1985-1999 OrCAD Inc.

important hits, and record them for classification and analysis. Although TOTRIB is not completed, we expect the finish board to accomplish its purposes.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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