2 The Neutrino Beam and Detector

A high-energy, accelerator-based neutrino experiment has two requirements: a beam of neutrinos and anti-neutrinos, and a detector capable of measuring the properties of neutrino interactions. Complicating both of these requirements is how rarely neutrinos interact. These particles do not interact electromagnetically, so it is not possible to accelerate or steer a neutrino beam. Because the weak interaction is very weak, the neutrinos' mean free path in any material is very large, making their detection a challenge.

Therefore, in general, neutrino detectors are massive—hundreds of tons—and neutrino beams are intense, in order to raise the probability of a neutrino interaction to something appreciable. The detector is both the target in which the neutrinos scatter and the instrument that measures the properties of the neutrino events. The neutrino beam is a tertiary beam, produced when a secondary beam of mesons is allowed to decay in flight. The meson beam is produced by a primary proton beam. Since protons are readily available, and are stable, charged, and strongly interacting, this produces a large number of mesons. Since neutrino experiments are so large in scale, they require the collaborative effort of many people. There are several large accelerator laboratories where high-energy neutrino experiments have been performed: Fermilab, in Batavia, Illinois; Argonne, in Argonne, Illinois; Brookhaven, in Upton, New York; and CERN, located in Geneva, Switzerland.

The experiment presented in this thesis was performed at the Fermi National Accelerator Laboratory. Fermilab's 800 GeV proton beam was used to produce a wide-band beam of neutrinos and anti-neutrinos, which remains the highest-energy neutrino beam yet produced. The experiment was done with the CCFR detector, located in Lab E, one of several experimental areas in the Fermilab neutrino beam line. The detector consists of a 690-ton sampling calorimeter and a muon spectrometer. The data were gathered in two runs: E744 ran from February to August 1985 and E770 started in June 1987 and concluded in February 1988.

This chapter describes the experimental apparatus: the accelerator facilities at Fermilab, the neutrino beam, and the CCFR detector. The final section of this chapter describes the triggering criteria and the data processing.

2.1 Neutrinos at the Fermilab Tevatron

The experiment benefited from taking place at the Fermilab Tevatron, the highest-energy accelerator in the world at the time of this writing. During the experiment, 800-GeV protons produced a beam of neutrinos and anti-neutrinos with an average energy of about 140 GeV, with maximum neutrino energies going as high as 600 GeV. A schematic diagram of the Fermilab accelerator complex is shown in Figure 2.1. Below is a description of the various stages used to accelerate the proton beam:

- ION SOURCE: H^- ions are produced by a cesium cathode immersed in hydrogen gas.

- COCKROFT-WALTON ACCELERATOR: The Cockroft-Walton is an electrostatic machine which begins the proton acceleration process. By employing multiple electrostatically-induced potential drops, the ions are collected from the source and accelerated to 750 keV.

- LINAC: A linear accelerator, consisting of a chain of radio-frequency cavities, increased the energy of the H^- ions to 200 MeV. As the ions exit the LINAC they pass through a carbon foil, which strips them of their two electrons.

- BOOSTER: The Booster is a 140 *m* diameter synchrotron. A synchrotron is a ring-shaped machine in which an applied magnetic field maintains the protons in the proper orbit while an accelerating RF electric field is provided at gaps along the ring. As the particles gain energy, the magnetic field is increased to preserve the orbit while the frequency of the accelerating electric field also increases. The Booster accelerates the protons to 8 *GeV* and injects them into the main ring.

- MAIN RING: The main ring is a 2 *km* diameter synchrotron that accelerates the protons to 150 *GeV*. It contains 1000 conventional, copper-coiled magnets to bend and focus the protons. Prior to construction of the Tevatron ring, the main ring served as Fermilab's primary accelerator.

- TEVATRON RING: The Tevatron is a superconducting proton synchrotron. It shares the tunnel with the main ring and is positioned immediately below it. The Tevatron's superconducting magnets operate in the temperature range of liquid helium and provide a 40 *kG* field. The accelerator was designed to accelerate particles to 1 *TeV*. During this experiment, the protons were accelerated to 800 *GeV*, a choice of energy that optimized the machine performance.

When operating in fixed-target mode (as opposed to collider mode) the Tevatron operates on a 60-second cycle. During each cycle the Tevatron is filled with approximately 10^{13} protons. The protons are held at their maximum energy for about a third of the cycle and extracted in fast and slow spills. The fast spills are called pings and are of millisecond duration while the slow spills last two seconds. Protons from slow spill are directed to other experiments, while the pings are used to create the neutrino beam.

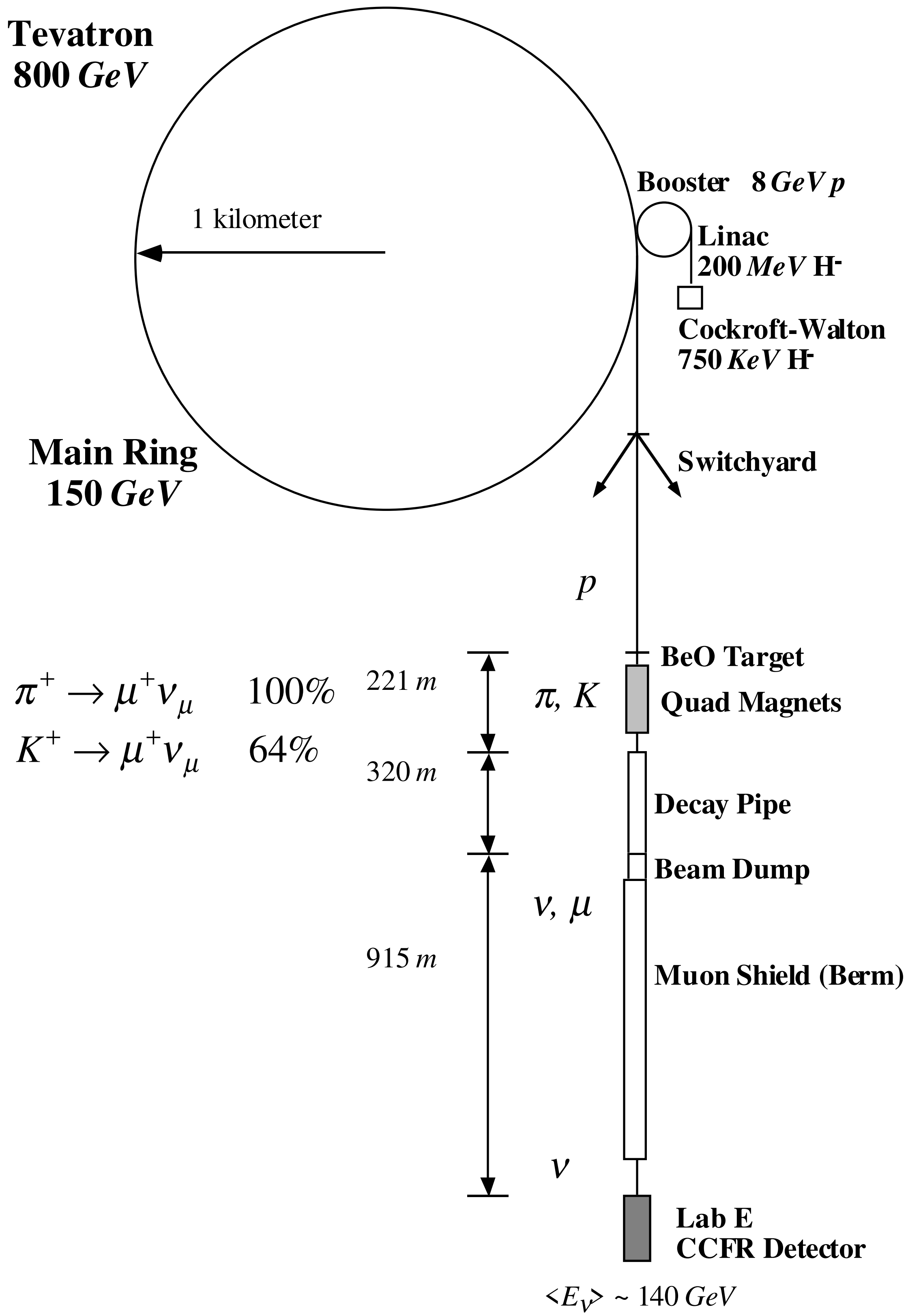

Figure 2.1: Fermilab neutrino beamline layout.

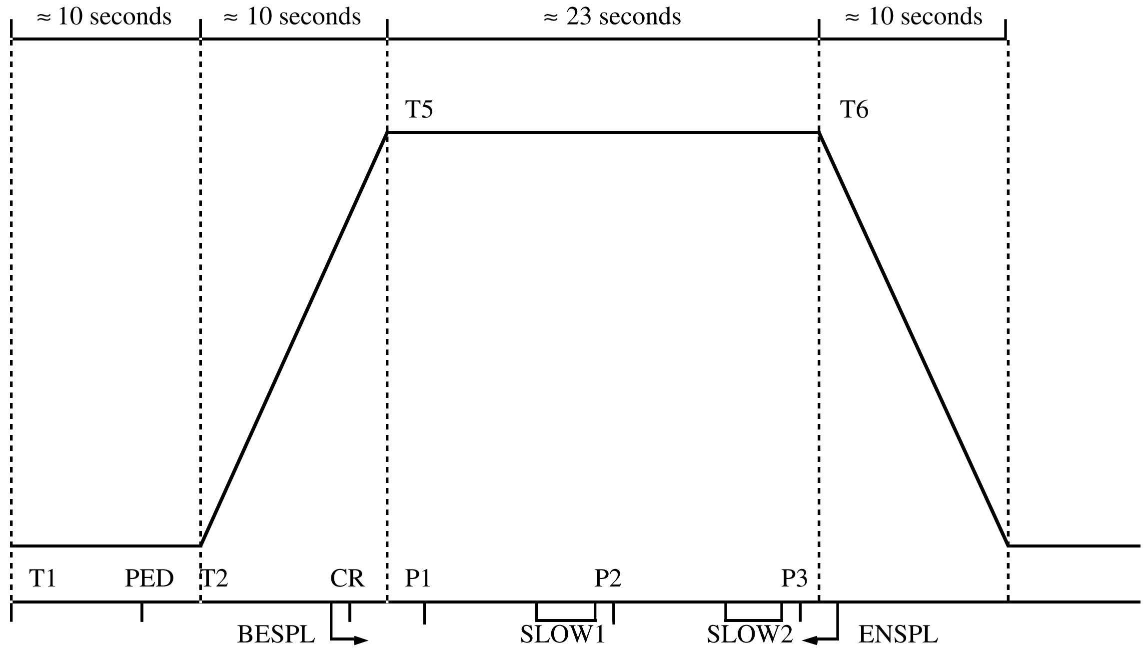

Figure 2.2: Tevatron magnet current versus time during fixed-target operation. The magnet cycle is described in the text.

The timing structure of the Tevatron magnets is shown in Figure 2.2. The cycle begins at time T1. The Tevatron is filled with protons that have been stored in the main ring and after ten seconds, at time T2, the current in the Tevatron magnets begins to ramp up, and the protons are accelerated. The increase in the magnetic field is synchronous with the increasing RF frequency. After 10 seconds and approximately 10^{13} revolutions, the protons reach 800 *GeV*. The beam is stored at this energy for 23 seconds, between T5 and T6, while the protons are extracted. P1, P2, and P3 indicate the fast spills, while two slow spills are extracted between them. At T6 the magnets being to ramp down and the cycle repeats.

2.2 Neutrino Beam

For neutrino production, the proton beam was directed onto a 33 *cm* long (1 interaction length) beryllium-oxide target in the Neutrino Center beamline. A secondary beam of mesons emerges from the target and is focused by a triplet of quadrupole magnets. The secondaries enter a 320 *m* decay region 221 meters beyond the target. Pions and kaons decay in flight, with dominate decay modes:

$$\pi^+ \to \mu^+\nu_\mu,\ \pi^- \to \mu^-\overline{\nu}_\mu \qquad \text{BR} = 99.99\% \tag{2.1}$$

$$K^+ \to \mu^+\nu_\mu, K^- \to \mu^-\overline{\nu}_\mu \qquad \text{BR} = 63.5\% \tag{2.2}$$

The maximum neutrino energy is governed by the mass ratio of the muon and the decaying particle:

$$E_\nu^{\max} = E_{\pi,K}\left[1-\left(\frac{m_\mu}{m_{\pi,K}}\right)^2\right] \tag{2.3}$$

so that the neutrino beam exhibits a dichromatic spectrum, with the more energetic muons coming from the kaon decays:

$$\left(E_\nu^{\max}\right)_K = 0.95\,E_K \tag{2.4}$$

$$\left(E_\nu^{\max}\right)_\pi = 0.43\,E_\pi \tag{2.5}$$

The Fermilab Neutrino Center beamline is shown in Figure 2.3. Event timing is initiated by a signal pulse as the proton bunch passes through a toroid (NC1TOR) upstream of the target. After the BeO target, the focusing of pions, kaons, and other charged particles is done by a triplet of quadrupole magnets, NC1Q4 through NC1Q6. The triplet serves to gather the mesons off the target and collimate them into a parallel beam in the decay region. To gain maximum acceptance, no sign or momentum selection is done, and the beamline is configured as a *wide-band beam* with large momentum acceptance.

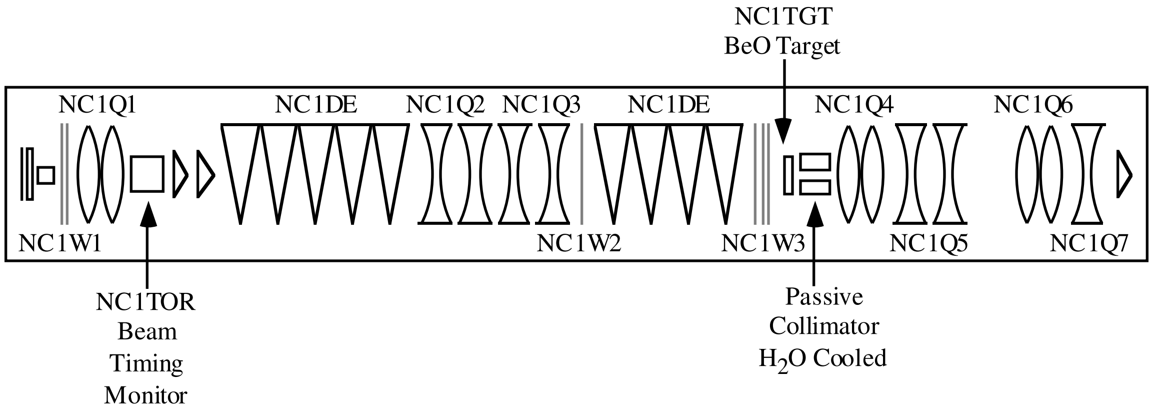

Figure 2.3: Neutrino Center beamline. Dipole magnet are indicated by prisms (triangles), and quadrupole magnets are indicated by concave and convex lenses.

Approximately one-tenth of the mesons decay in the decay region and the remainder of the beam is dumped into a 6 *m* block of aluminum followed by steel shielding. The CCFR detector is positioned 915 *m* beyond the dump. The muons and neutrinos that penetrate the aluminum beam dump encounter approximately 241 *m* of steel shielding and 582 *m* of earth berm before reaching the detector. The amount of material in front of the detector is sufficient for the muons from the meson decays to range out, so that of all the particles entering the berm, only the neutrinos penetrate into the experimental areas. However, neutrinos may interact inside the berm, and a small number of berms muons also enter the experimental hall. Events due to muons are identified and discarded by their interaction in the veto wall, a set of scintillation counters positioned upstream of the target calorimeter. The front face of the CCFR detector is 915 *m* from the end of the decay region, and neutrinos strike the detector within about a one meter radius around the beam axis. Therefore, the neutrinos have an incident angle no larger than about 1 *mrad*, allowing the good approximation that neutrinos strike the target at normal incidence. The procedure used to determine the neutrino flux is described in Chapter 5 and the relative neutrino and anti-neutrino flux is shown in Figure 5.9.

2.3 Detector and Trigger

The following sub-sections describe each of the elements of the CCFR detector and trigger system. Figure 2.4 shows a schematic of the detector. Figure 2.5 shows the appearance of a charged-current event as seen by the elements of the apparatus.

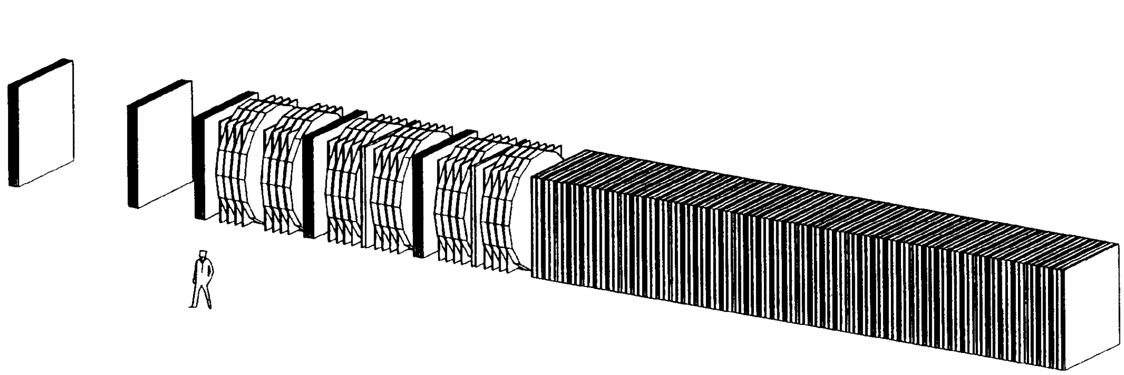

Figure 2.4: Schematic representation of the CCFR detector. The neutrino beam enters from the right. The target calorimeter is on the right and muon spectrometer is on the left. The two leftmost banks of drift chambers are known as the blue cart.

2.3.1 Target Calorimeter

The target calorimeter is a steel-scintillator large-area calorimeter that also includes drift chambers for charged-particle tracking. It has a mass of 690 tons, is 17.7 *m* long and measures 10 feet by 10 feet transversely. It is made up of six identical modules called carts. Each cart contains 28 steel plates, seven drift chamber stations, and fourteen scintillation counters. Each steel plate is 5.15 *cm* thick. A liquid scintillation counter is positioned between every two plates and a drift chamber is placed between every four plates. Each scintillation counter occupies 6.48 *cm* along the beam axis, and each drift chamber station occupies 8.87 *cm*. A schematic view of one cart is shown in Figure 2.6.

The carts are numbered so that cart 6 is the most upstream and cart 1 is the most downstream. The counters are numbered so that counter 84 is the most upstream.

2.3.1.1 Scintillator Counters

The energy sampling fraction of the calorimeter is approximately 11%. The measurement is made by scintillation counters, which are acrylic tanks measuring 10×10 feet by 1 inch filled with mineral oil doped with scintillating fluors. A photomultiplier tube (PMT) at each corner of the square counter is used for readout. Each counter is enveloped in opaque material to prevent external light from reaching the phototubes, and plastic bags filled with water occupy the space between the counters and the steel plates to balance the pressure on the acrylic walls. Figure 2.7 shows a sketch of a scintillation counter.

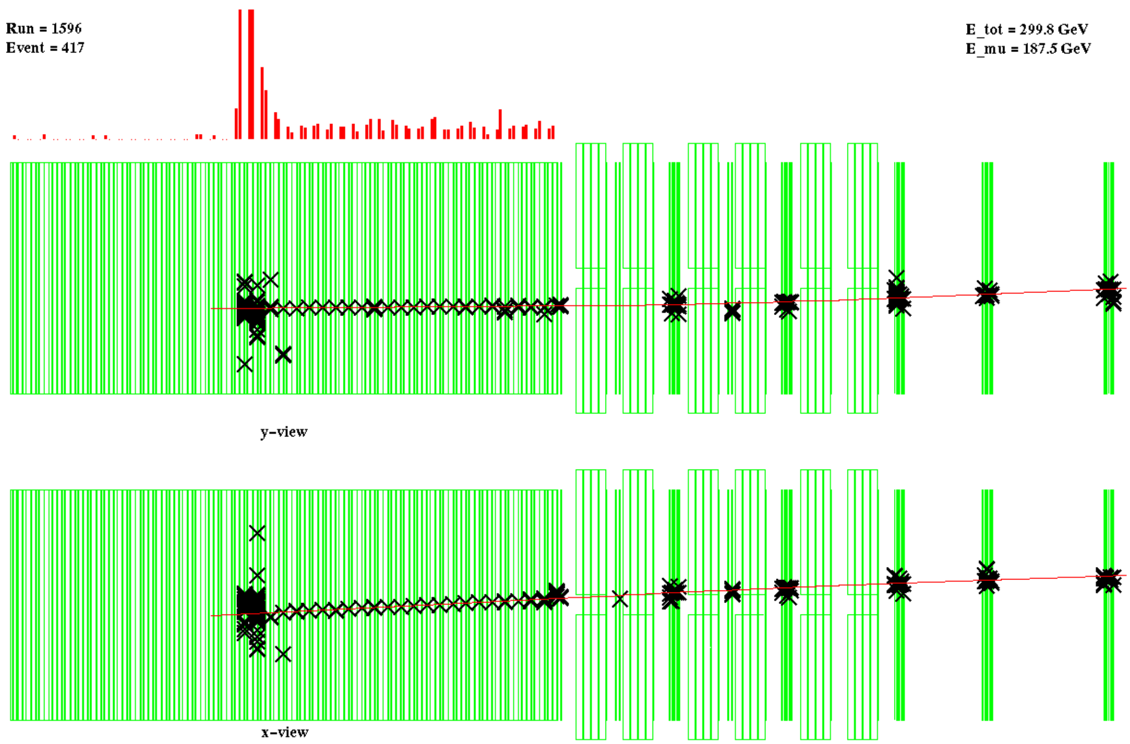

Figure 2.5: A typical charged-current event as seen by the elements of the CCFR detector. Hits in the drift chambers are shown as "X". Pulse heights in the calorimeter scintillators are shown in a logarithmic scale above the target. The line linking the hits in the target and the toroid is derived by the tracking software as described in Chapter 3.

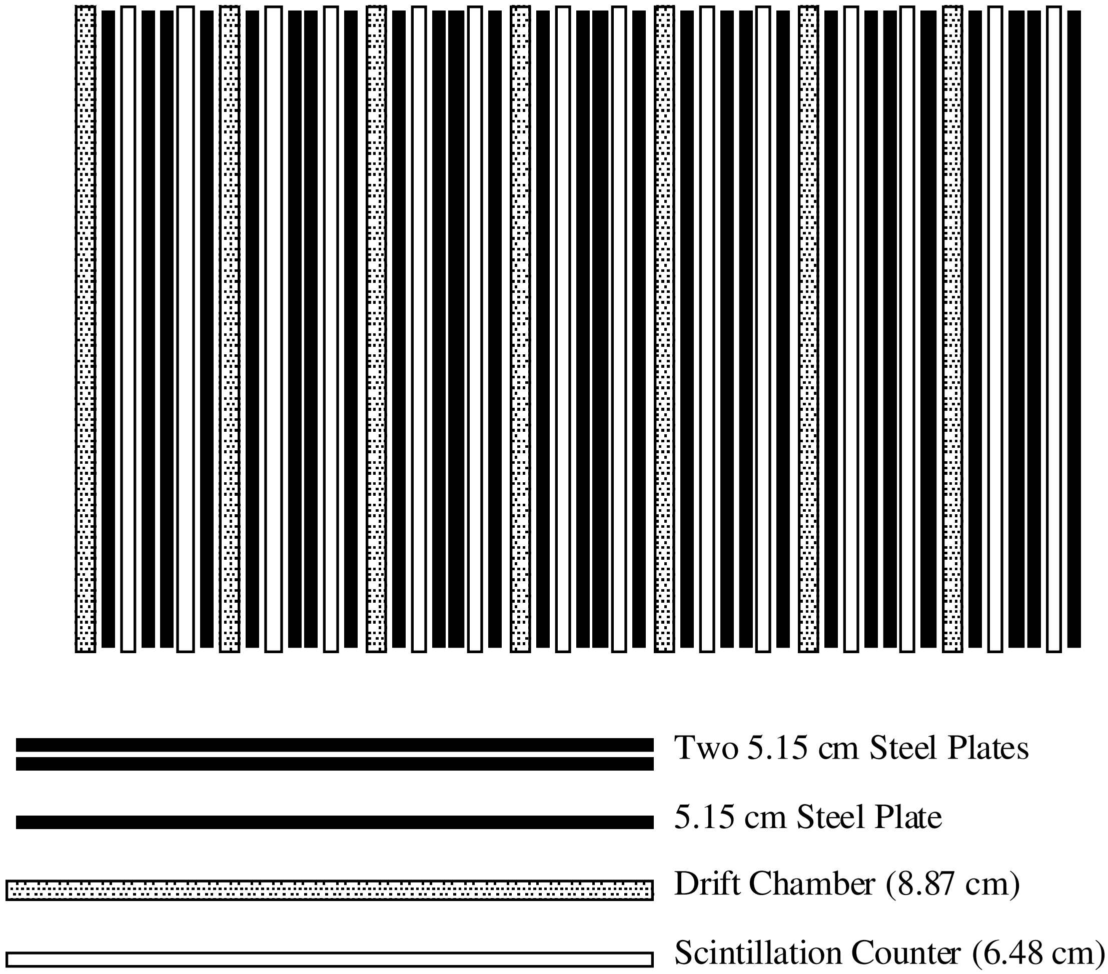

Figure 2.6: Stack layout of a CCFR target cart. A drift chamber is positioned after every two steel plates and a scintillation counter is found after every four.

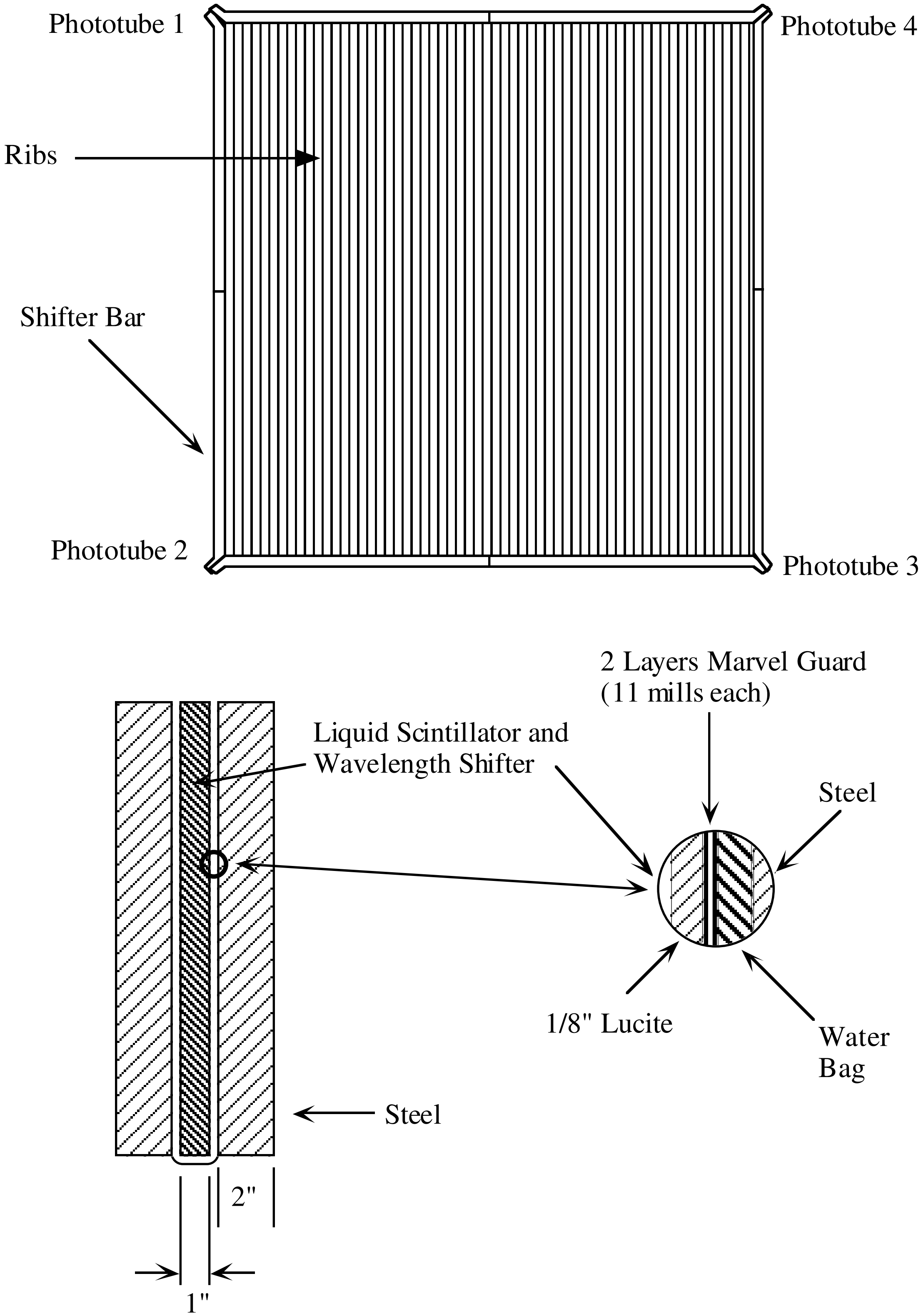

Figure 2.7: CCFR scintillation counter.

A charged particle passing through the counter excites primary fluors in the oil, which radiate ultraviolet light. The ultraviolet light is absorbed by secondary fluors in the oil, which emit visible blue light. The blue light has a longer attenuation length in the oil, about 40 inches, and light emerging below the critical angle is transmitted to the edges of the counter through total internal reflection. At the edges there are one-half-inch-thick BBQ-doped plastic bars that absorb the blue light and re-emit green light. Finally, the green light is guided to the ends of the bars where the phototubes are positioned.

Each counter has four RCA 6342A phototubes, which were operated with a potential drop of 1400 volts across the cathode. A photon striking the cathode has about a 20% probability of liberating an electron. The tube multiplies this signal with a series of ten dynodes, each dynode emitting four electrons for each one absorbed. A single initial photoelectron produces a signal of about 0.25 picoCoulombs. The sensitivity to a muon traversing through the center of a counter is about 2.5 photoelectrons per phototube.

The phototube signal is digitized by a LeCroy 4300 FERA, a fast and buffered readout system with analog-to-digital converters with 11 bits of dynamic range. The counter readout has seven ADC channels of differing sensitivity and the phototube signal is fanned out, giving the system an effective dynamic range of 19 bits. One counter's readout is shown in Figure 2.8. The gate width of the ADCs is 244 *nsec*, beginning 30 *nsec* before the leading edge of the phototube signal, for an integration time of 215 *nsec*. The charge collected is stored on a capacitor and the digitization is accomplished by measuring the time required to discharge the capacitor through a resistor. Digitizing the signal requires 8.5 μsec and another 3.2 μsec is needed to buffer the data, leading to a dead time of 11.7 μsec. A pedestal voltage of approximately 50 counts is applied to each ADC. This pedestal is recorded every accelerator cycle, before the first ping, by taking twenty fake events, so that it can be subtracted from the data readings.

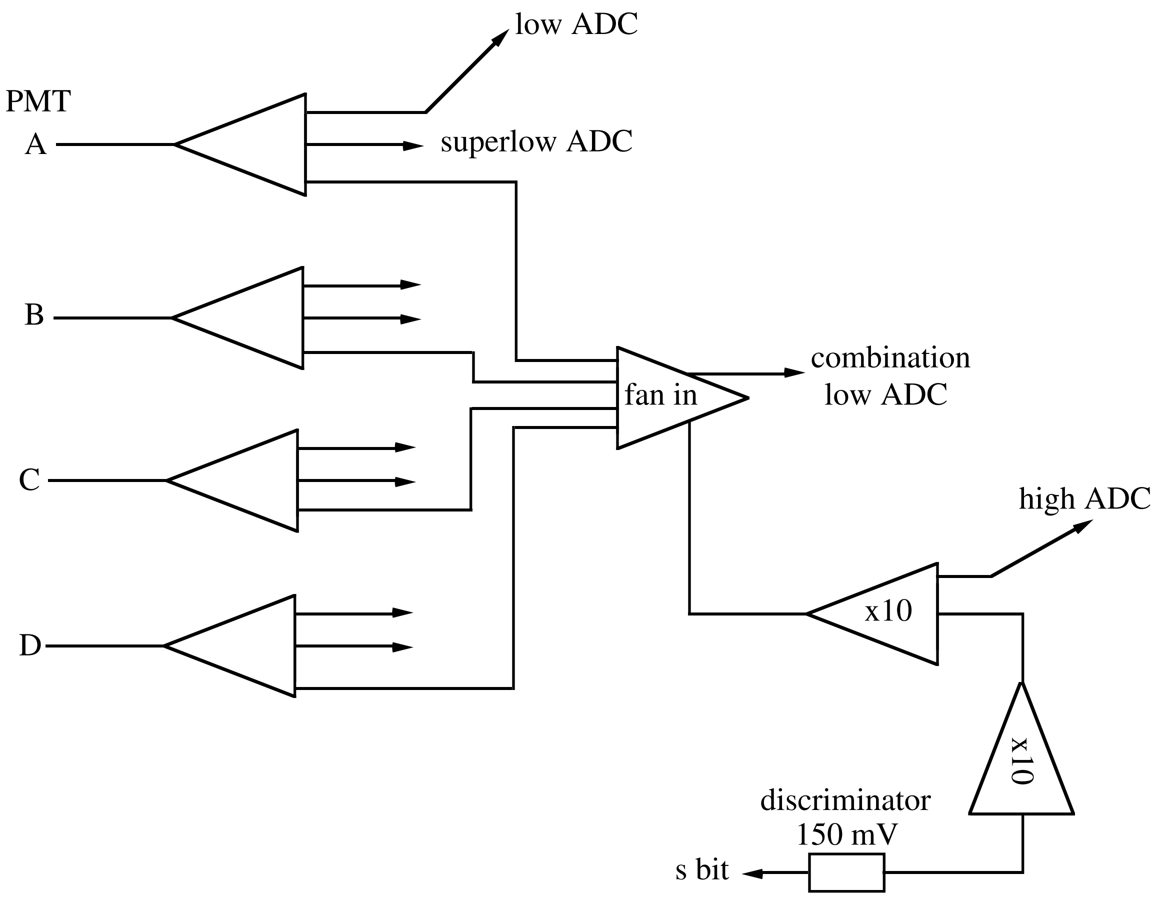

Figure 2.8: Readout electronics for a single scintillation counter. Each counter's signal is digitized by seven ADC channels, as described in the text. The threshold of the s-bit discriminator is set at one-quarter of minimum-ionizing level.

The analog phototube outputs from each counter are fanned out and digitized by seven ADC channels of differing sensitivity:

- There are four LO channels A_j^{LO}, one for each of the j phototubes in a counter. A muon passing through the center of a counter will typically produce 2 ADC counts at each LO channel.

- The combination-low (or COMBLO) channel A^{COMBLO} is the analog sum of the four LO signals. A muon yields 8 ADC counts at this channel.

- The HI channel A^{HI} is the sum of the four LO signals amplified by a factor of ten. The muon signal at this channel is 80 counts.

- The super-low $A_j^{SUPERLO}$ is a sum of LOs from phototube j from every tenth consecutive counter, attenuated by a factor of ten. The typical muon signal at this channel is 0.2 counts.

The signals are so digitized to maximize the dynamic range. A hadron shower will typically produce 1000 to 2000 counts in one counter and be measured directly by the LOs. In the event of an overflow (greater than $2^{11} - 1 = 2047$ counts) the SUPERLO is used to measure the energy deposit. The HI channel is used to measure the passage of a muon, whose signal is too small to be measured by the LOs. Important for triggering, the COMBLO channel is used to produce a logical signal known a scintillator-bit or s-bit, when the COMBLO signal is greater than one-quarter minimum-ionizing level (see Figure 2.8).

At the Tevatron, the accelerator rf buckets arrive in intervals of 18.6 *ns*. Event timing is measured at each counter using the same time-to-digital converters (TDCs) that are used for the drift chambers (see the next Section). Each counter's s-bit pulse is fed to the TDC, providing a time resolution of 4 *nsec*. When information from all active counters is combined, the overall event time resolution has an rms of 2.4 *nsec*.

2.3.1.2 Drift Chambers

Muons emerging from the neutrino interaction are tracked inside the calorimeter target by drift chamber stations. A drift chamber records the passage of a charged particle by detecting the liberation of ionization electrons. Each drift chamber station has an active area of 10 square feet and is comprised of 24 horizontal and 24 vertical cells. Each cell is

5 inches across and 0.75 inches thick and contains three wires. Figure 2.9 shows a sketch of a drift chamber cell.

Each chamber is constructed of Hexcel-covered aluminum walls. Parallel aluminum I-beams spaced every five inches support G-10 cover plates and define the drift chamber cells. Within each cell, a 127 μm diameter copper-beryllium central field wire is held at +350 volts. Two 30 μm diameter gold-plated tungsten wires run on either side of the field wire and are held at +1750 volts. Nylon spacers placed every 12 inches maintain 2 *mm* spacing between each sense wire and the field wire. The I-beams are maintained at –4500 volts. Finally, the inside of the G-10 cover within each cell is clad with 19 copper cathode strips, each of which is held at a particular voltage so that a uniform electric field of 690 volts/*cm* is created.

The chambers are filled with an equal mix of argon and ethane. A noble gas, argon does not form molecules and so lacks vibrational or rotational modes of excitation. Therefore, argon readily ionizes when excited by a passing energetic charged particle. After the primary ionization, the electrons and ions separate due to the applied electric field. The electrons drift toward the anode sense wires and accelerate, producing secondary ionizations. Ethane, an organic compound, is included to render the chamber self-quenching. That is, the ethane absorbs the ultraviolet photons liberated in the argon as the electrons drift towards the sense wires. This limits the avalanche of charge that would otherwise smear the signal pulse.

The drift velocity of electrons in the drift chamber is 50 $\mu m/nsec$, so that the total drift time to cross 2.5 *in* inside a cell is 1.3 μsec. The arrival time of the drift chamber pulse on one wire relative to the event time allows the determination of the particle's position in one dimension, up to the ambiguity of knowing on which side of the wire the particle passed. Having two sense wires per cell resolves this ambiguity, as the wire closer to the particle received the ionization first. Combining the hit information from two adjacent orthogonal cells proved the determination of the particles' position in the *x*-*y* plane.

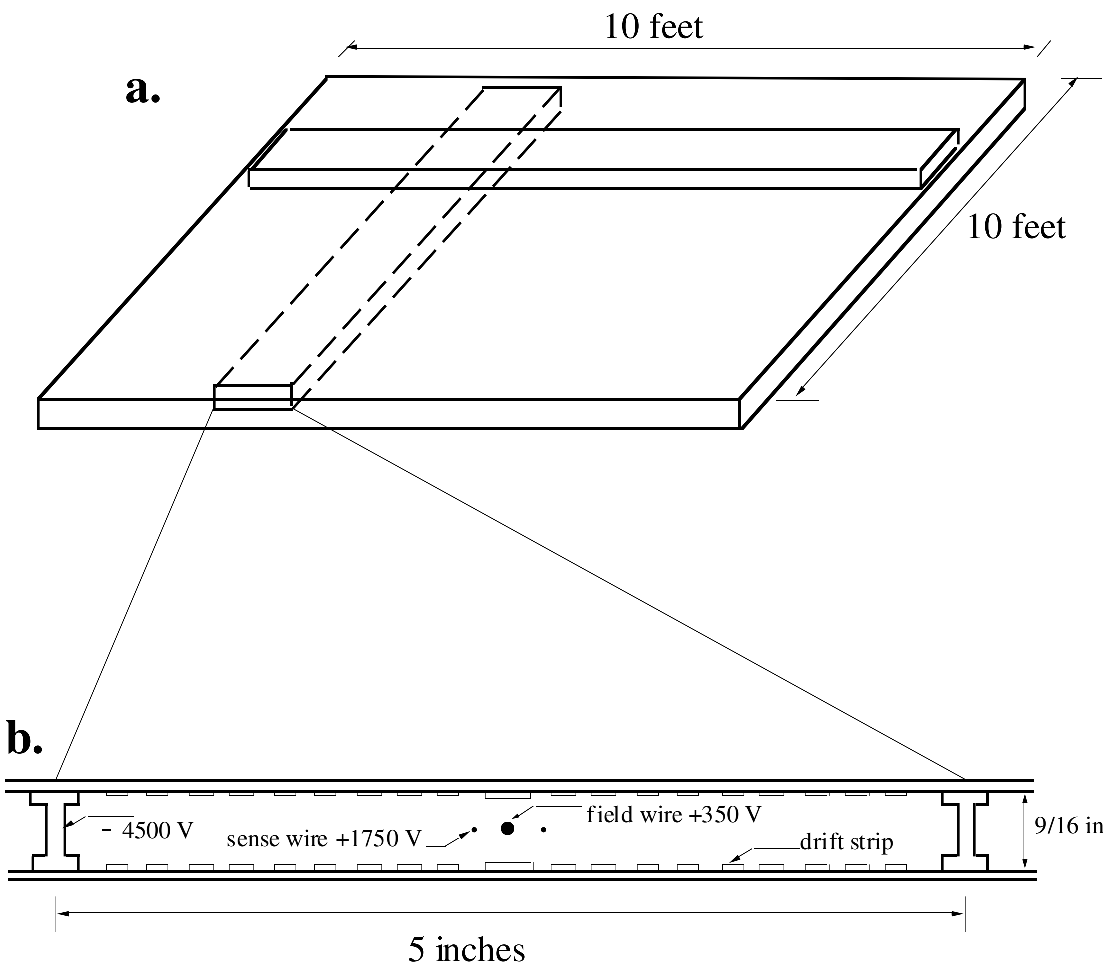

Figure 2.9: Sketch of CCFR target drift chamber section. **a.** Diagram of one chamber. There are two orthogonally-oriented planes per station, consisting of three-wire cells. **b.** A three-wire drift-chamber cell.

The signal from the sense wires is amplified and sent to two coupled TDCs, which have their 8 *nsec* time bins staggered by 4 *nsec*. Thus the coupled TDC digitizes the time of the pulse in 4 *nsec* bins. The TDC is capable of buffering hits in 512 bins, so its live time is slightly in excess of 2 μsec and so can buffer the full drift range of the cell. The TDC then takes 8 *nsec* to transfer its information into a first-in-first-out (FIFO) buffer. The FIFO buffer can store 32 events per spill.

The overall position resolution of the drift chambers depends on the time resolution of the TDCs, variations in the electric field, and misalignment of the chambers. All elements of the detector were aligned with an optical survey, and precise alignment of the chambers was accomplished by using high-energy straight-through muons with $p_{\mu} > 125$ *GeV*. The alignment procedure iteratively varied the chamber coordinates to provide the best fit to the sample of straight-through muons. In the target, such an alignment procedure was straightforward because the target is unmagnetized, and the effects of multiple Coulomb scattering (described in the next Chapter) diminish with energy. The intrinsic position resolution of the target drift chambers is 225 μm.

2.3.2 Muon Spectrometer

Downstream of the target calorimeter lies a muon spectrometer consisting of three large toroidal iron magnets instrumented with acrylic counters and with arrays of 10-square-foot- drift chambers. Each of the three instrumented magnets is referred to as a toroid cart. A sketch of a typical toroid cart is shown in Figure 2.10. Each toroid cart is segmented into eight 8-inch-thick cylinders, called washers, each with a 70-inch outer radius and a 5-inch inner radius. Each washer is divided horizontally into semicircles separated by 0.95 *cm* with aluminum spaces to allow insertion of a Hall probe. The bottom of each washer includes two iron legs that support the magnets on movable platforms.

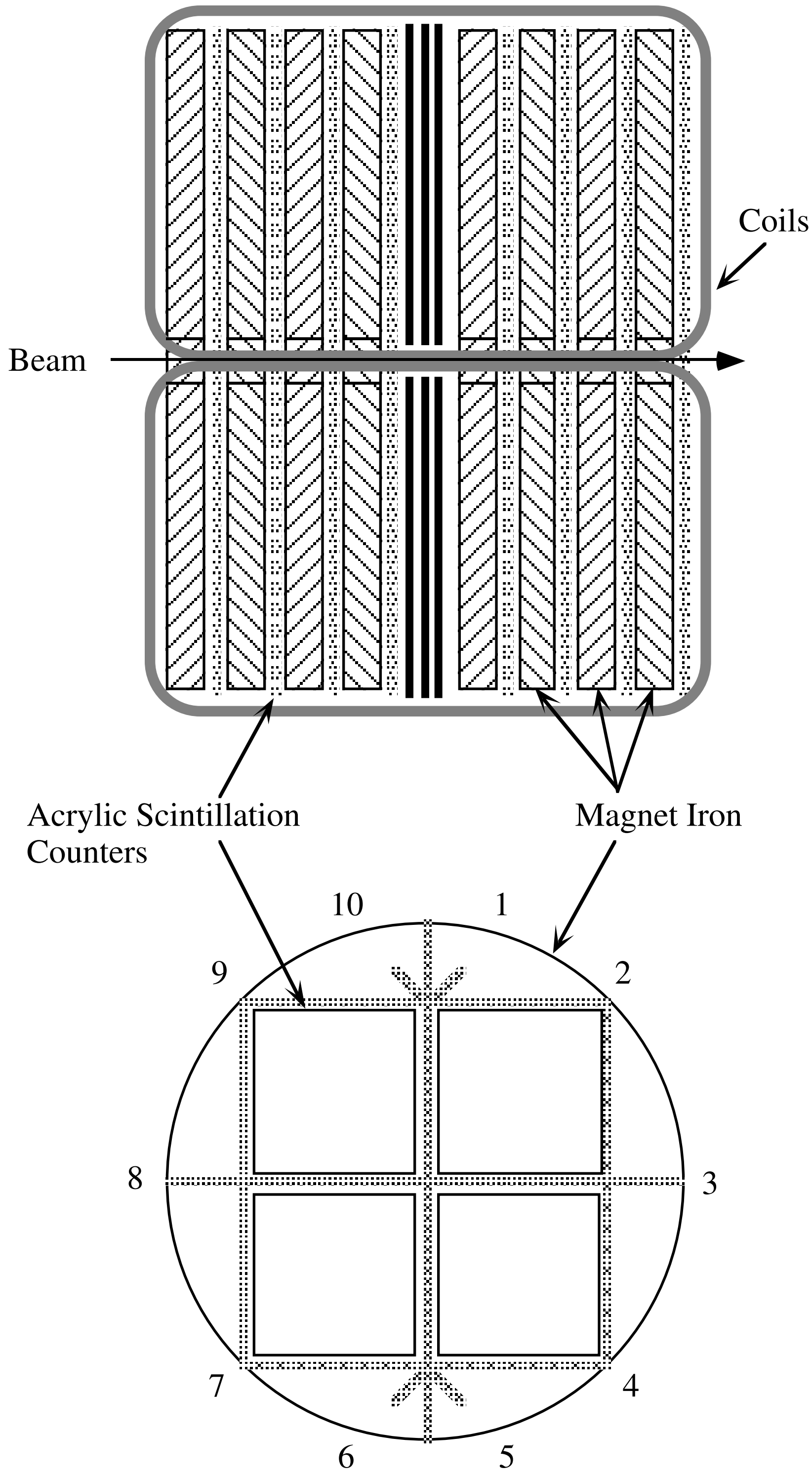

Figure 2.10: Schematic drawing of a CCFR toroid cart, showing overhead and transverse views. In the transverse view, the shaded liens indicate the wave shifter bars along the outer edges of the scintillators, and the numerals indicate the positions of phototubes.

Four copper coils of 12 turns each encircle the magnets at 90˚ intervals. A current of 1200 *A* produces a magnetic field ranging from 1.9 *T* near the center of the toroid to 1.55 *T* near the outer edge. The field was found to be azimuthal throughout the magnets except for a small radial component at the iron legs [Kin91]. A muon traveling the length of the spectrometer receives a 2.4 *GeV* transverse momentum component from the magnetic field.

Tracking muons through the spectrometer is accomplished by five sets of the five drift chambers, positioned immediately downstream of each toroid cart and 3 *m* and 7 *m* behind the last toroid. The two most downstream sets of drift chambers are referred to as the blue cart. The drift chambers in the muon system contain one-wire cells. To resolve the left-right ambiguity, the chambers are staggered by 1/4 of a cell width. This staggering method is possible in the muon spectrometer because successive drift chambers are not separated by steel, as they are in the target, making the effects of multiple Coulomb scattering between chamber planes negligible. Muons are tracked cleanly through the set of five drift chambers, allowing the five to be treated as a unit.

In addition, there are two *u-v* drift chambers, whose orientation is rotated 5˚ about the beam axis. One is located immediately downstream of the target and the other included in the set of five chambers on the upstream side of the blue cart.

Alignment of the drift chambers in the toroid spectrometer using straight-through muons was more complicated than in the case of the target calorimeter because of the bending of tracks in the spectrometer's magnetic field. A description of the alignment procedure can be found in Ref. [Rab92]. The alignment of the toroid drift chambers was accomplished to within 380 μm, and the overall position resolution of these drift chambers is 0.5 *mm*.

The muon spectrometer is instrumented with acrylic scintillation counters, and for fast detection of muons for triggering. One set of counters, called T2, is located just after the first toroid cart (in gap 1), and another set, T3, is after the second cart (in gap 2). T2 is composed of a total of 10 counters, organized into three planes, and T3 is made up of six counters, organized into two planes. These counters are equipped with 56AVP phototubes. The first two T2 planes and both T3 planes are composed of two narrow counters, referred to as hodoscopes, and one large counter. The final T2 plane is composed of four hodoscopes. Usually, the term "hodoscope" refers to a counter system capable of making a good determination of particle position. In this case, no measurement of position is made. The trigger condition for the gap is satisfied if any counter in the gap fires its s-bit.

There is an acrylic counter plane positioned after every washer. Each of these planes is divided into four separate counters, so that the quadrant through which the muon traveled is determined. The four planes in one half-cart are grouped together. These counters, forming 24 planes in all, are used to define the PTOR trigger condition, which is described below.

2.4 Data Acquisition

The CCFR detector (the target calorimeter and muon spectrometer) records the raw data of a neutrino event. These raw signals—the pulse heights from the scintillation counters, the drift chamber hits, the timing pulses—must be converted to physical quantities like muon energy, muon angle, and hadronic energy. In the process, the data is reduced to select the events of interest, while discarding events due to background or noise.

2.4.1 Event Triggers

The first step in concentrating on events of interest is to record only those that satisfy basic requirements or *triggers*. The satisfaction of a trigger causes the data acquisition system to accept the event and record the full detector response. A subset of the detector is used to define the trigger, using scintillator signals that can be processed quickly. Each trigger rigorously defines an event signature that can be used to discriminate between different types of events. The triggers are designed to accept charged-current and neutral-current neutrino events and other specific events of interest while rejecting cosmic ray and beam-related backgrounds.

The beam-related backgrounds are caused by charged particles emanating from the berm, due to neutrino interactions in the berm. Two 17.5×4.5 m scintillation counter arrays are positioned immediately upstream of the first calorimeter cart to form a veto wall. The veto wall counters are shielded from an upstream flux of low-energy hadrons and photons by a one-meter-thick concrete wall, and lead sheets are mounted between the two scintillators of the veto wall. During beam running, secondary particles from the berm interact with the air above the detector and illuminate the detector with low-energy photons. A layer of lead bricks is stacked above the toroid gaps to shield the trigger counters.

The muon trigger hardware consists of scintillators located in the muon spectrometer. The T2 and T3 counters, located in the gaps between toroid carts, are used to define the charged-current event trigger. The acrylic counters positioned after each of the spectrometer's 24 magnetic washers are used to define the PTOR condition, used for Triggers 4 and 6. Six separate triggers were used during the runs:

- **Trigger 1** (Charged Current): This trigger is designed to selected charged-current events. It attempts to select events in which a muon originates in the target and penetrates into the toroid for momentum analysis. This trigger requires the presence of a charged particle in the last target cart and in the first toroid cart, while requiring no activity in the veto wall. Either of two topologies must be satisfied: In the first, at least two out of the last four counters (counters 1 through 4) fire their s-bits, and a minimum-ionizing signal is record in both T2 (toroid gap 1) and T3 (gap 2). The second trigger definition does not require the muon to penetrate to T3 but demands the firing of two s-bits out of target counters 9 through 12.

- **Trigger 2** (Neutral Current): This trigger is designed to select neutral-current events, which are events in which a Z^0 is exchanged to create a hadronic shower without a muon track. It demands that there be at least 8 *GeV* of energy in 8 adjacent counters, coincident with 2 MIPs deposited in two counters out of a set of four consecutive counters, and no signal in the veto wall. No muon requirement is made.

- **Trigger 3** (Penetrating Muon): This trigger is used to study muons ranging out in the calorimeter. It requires that 16 counters in the target (not necessarily consecutive) fire their s-bits with no veto, along with 4 *GeV* of hadronic energy deposited in a set of 8 consecutive counters (not necessarily those that fired their s-bits).

- **Trigger 4** (Redundant Charged Current): This trigger was used to measure the Trigger 1 inefficiency, and found it to be $< 10^{-4}$. It is similar to Trigger 1; instead of counters 1 through 4 and counters 9 through 12, it uses counters 5 through 8 and 13 though 16. Instead of using T2 and T3, Trigger 4 requires that PTOR be satisfied, which is that two out of four acrylic counters in the same quadrant in each of the halfcarts fire their s-bits. Since Trigger 4 makes this stricter requirement than Trigger 1, all of the Trigger 4s should be included in the Trigger 1 sample.

- **Trigger 5** (Test Beam): The use of this trigger is reserved for test beam running, when muon and hadron beams are directly incident on the target.

- **Trigger 6** (Straight-Through Muon): This trigger is designed to select muons produced upstream of Lab E that pass through the entire detector. One s-bit out of a set of four in each of the target carts must fire, along with the veto, and the muon must penetrate the toroid system and satisfy the PTOR requirement. The stiff muon tracks passing this trigger are used for calibration and drift-chamber alignment. In E744 this trigger was prescaled down by a factor of 8. In E770 the trigger was generally not prescaled in order to accumulate additional events for counter energy calibration.

2.4.2 Data Collection

The raw data collected in both runs of the experiment fill about 1000 open-reel tapes, comprising approximately 300 gigabytes of information. The number of events recorded according to trigger type is listing in Table 2.1.

Once written on tape, the data passed through several stages of offline processing, which ultimately reduced it to data summary tape (DST) format. The raw data's first pass was through a process called stripping, which unpacked ADC pulse heights and subtracted their pedestal values, and otherwise rewrote the data in a modified format. The second-pass data analysis passed the stripped data through a program called the cruncher, which did the bulk of the processing to extract the events' characteristics: pulse heights were converted to hadron energies, TDC times to hit positions. A pattern-recognition algorithm fit muon tracks to the hit positions, leading to a determination of the muon angle and energy. The final event observables—the hadron energy, the muon angles and energies, and secondary variables like x and y—were written to a DST. The DST file contains the basic set of data used for physics analysis.

Event reconstruction, writing DSTs, and the final physics results are all predicated on the ability to measure the absolute hadron shower and muon angles and energies, the parameters that define a charged-current deep inelastic scattering event. The next chapter describes the detector calibration: the process that determines the precise number of ADC counts that correspond to 1 GeV of hadronic energy, and the precise bend of a muon's trajectory that corresponds to a measurement of 1 GeV of muon momentum.

Table 2.1: Triggers written to tape in E744 and E770. An event can satisfy more than one trigger.

Trigger Type	E744	E770
1	1740427	1981136
2	2267724	2915707
3	1611230	2001988
4	696664	806985
5	16447	64627
6	166682	1406410
Total	3235717	5095487