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First Events and Prospects at the Fermilab Collider

CDF Collaboration*

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1 Abstract

A brief description of the Collider Detector at Fermilab (CDF) is given including the detector components and the data acquisition system. The first test run, the first events, and the performance of the detector are discussed. Finally the prospects for future running are reviewed.

2 Introduction

CDF is a large detector currently being assembled at the Fermilab Tevatron by an international collaboration of physicists from the U.S., Italy, and Japan. During September-October 1985, there was an engineering run to test the antiproton source¹ and the CDF data acquisition system. Significant parts of the CDF detector were in place and proton-antiproton collisions were observed at 1.6 TeV center-of-mass energy. Many of the detector components were not installed for this run because of time limitations and a temporary physical constraint imposed by the location of an accelerator beampipe 18 inches above the Tevatron. The constraint will be moved and the full detector will be in place for the next run scheduled for the winter of 1986-87.

3 Detector

An isometric view of the CDF detector is shown in figure 1. and a cut through one half the detector is shown in figure 2. The detector is built around a solenoidal magnet with an axial field (i.e. parallel to the beam direction). Inside the magnet

* The members and their institutions are listed in Appendix A.

¹J. Peoples, "Fermilab Antiproton Source," *IEEE Transactions on Nuclear Science* Vol. NS-30, No. 4 (Aug. 1983) p1970 ; G. Dugan, "TeV I, Energy Saver, and Anti-Proton Source," *IEEE Transactions on Nuclear Science* Vol. NS-32, No. 5 (Oct. 1985)

and in the forward direction there are tracking chambers, and behind these there are electromagnetic and hadronic calorimeters. In addition there are muon detectors, trigger counters, and small angle silicon strip detectors.

Small Angle Counters

Scintillation trigger counters and silicon microstrip detectors measure the charged tracks produced at small angles with respect to the beam. The trigger counters are a scintillation hodoscope surrounding the beam pipe that participates in the lowest level triggering. The sixteen trigger counters at each end of the detector cover the angular range from $5.8mr < \theta < 80mr$ and provide precise timing signals. These timing signals are used to provide the event timing for the TDCs and to measure the z position of the interaction vertex.

The silicon strip detectors are inside the beam pipe at positions ranging from 6 meters to 55 meters from the detector center and cover an angular range of $.2mr < \theta < 6.0mr$. They will be used to measure diffractive and elastic scattering, and in conjunction with the rest of the detector to allow a luminosity independent measurement of the total cross-section.

Magnet

The superconducting solenoidal magnet² is 3 meters in diameter by 5 meters long producing a 1.5 tesla field coaxial with the beam direction. The iron in the endplug and endwall calorimetry along with the yoke form the return path for the magnetic field; only a small part of the flux is returned through the central calorimetry iron. The magnet was not operated during the first test run because the accelerator constraints kept the endplugs from being installed, but it was tested earlier with the endplugs in place and performed well³. The magnet installation between the endwalls of the central detector is shown in figure 3.

Calorimetry

The calorimetry is characterized by a projective tower structure, good granularity, and good energy resolution; the specifics are summarized by the table shown in figure 4. The central detector and associated calorimetry are shown while in transit from the assembly area to the collision hall in figure 5. The central calorimetry has scintillator as the sampling medium in order to optimize energy resolution. In the forward direction ($\theta < 30^\circ$), all the calorimetry employs gas proportional tubes for sampling in order to minimize the effects of radiation damage. Considerable

²R. Wands, et al, "Design of an Indirectly Cooled 3-m Diameter Superconducting Solenoid with External Support Cylinder for the Fermilab Collider Detector Facility," IEEE Transactions in Magnetism MAG-19 (1983) p.1368 ; J. Grimson et al, "A 3-m Diameter x 5-m Superconducting solenoid for the Collider Detector at Fermilab," Proc. of the 12th Intl. Conf. on High-Energy Accelerators, Fermilab, Batavia, Illinois (1983), p. 639.

³R. W. Fast, et al, "Superconduction Solenoid for the Fermilab Collider Detector: Installation and Testing," Proc. of the 9th International Conference on Magnet Technology, Zurich, Switzerland (Sept. 1985) (to be published)

care has been taken in the design of the calorimetry to provide good gain monitoring systems and to make sure the calorimetry is hermetic. There also are "crack" counters covering the boundaries at constant ϕ between the central calorimetry wedges. They measure the position and energy of the electromagnetic showers pointing at these boundaries and eliminate a "hot spot" in the central hadronic calorimetry caused by these showers. The "crack" counters consist of 9 radiation lengths of uranium followed by a multiwire gas proportional chamber.

Tracking

There are three systems of tracking chambers. Together they measure all charged tracks down to approximately two degrees of the beam direction. Future plans include a silicon strip vertex detector surrounding the beam pipe.

Vertex Time Projection Chamber (VTPC)

The innermost tracking system consists of eight VTPC modules that surround the beampipe. An isometric view of two modules is shown in figure 6. Each module has two 15 cm drift regions separated by a center high voltage screen. The electrons drift from the center screen toward the endcap PWCs which are divided into 8 octants with 24 wires and pads each. The wires (chords of circles centered on the beam) measure points in the $r - \theta$ plane and are read out using multihit TDCs. The pads measure the position along the wire or the ϕ coordinate and are read out with FADCs. The active area extends from 6.8cm to 21.4 cm in radius and the total length in z of one module is approximately 35cm. The eight modules with a total of 3072 wires and 3072 pads are sensitive for particles with angles larger than $\theta \sim 3^\circ$. During the test run, only the wires were instrumented. Wire resolutions vary depending on drift distance and track angle but can be characterized as being the order of 500μ in the θ direction. Figure 7 shows the installation of these chambers for the fall 1985 test run. The data from these chambers for two good beam-beam interactions are shown in figures 8 and 9.

Central Tracking Chamber (CTC)

The CTC is a "jet type" axial drift chamber surrounding the VTPC that gives good resolution with a cell structure that facilitates pattern recognition. The chamber consists of 5 axial superlayers interspersed with 4 small angle stereo superlayers having a stereo angle of $\pm 3^\circ$. There are 12 sense wires in axial cells and 6 sense wires in stereo cells and the cells are tilted $\sim 45^\circ$ with respect to the radial direction. This tilt compensates for the $\sim 45^\circ$ Lorentz angle of the electrons drifting in the magnetic field so that the actual drift is perpendicular to the radial direction (i.e., perpendicular to the trajectory of high momentum particles). The sense wire spacing is $\sim 7mm$ in the radial direction and the maximum drift distance is $\sim 35mm$. The 6156 sense wires are read out with multihit TDCs. The length of the wires is 3214mm and the radii of the innermost and outermost sense wires are 309mm and 1320mm

respectively. The outermost superlayer covers the region $\theta \geq 40^\circ$ and the innermost superlayer covers $\theta \geq 14^\circ$. The single hit precision is $\sim 200\mu/\text{wire}$ and the two hit resolution is $< 5\text{mm}$. The momentum resolution is $\Delta P_t/P_t < .002P_t$ in GeV for primary tracks that pass through all superlayers.

At the outer edge of the CTC, there are also three layers of axial drift tubes ($\sim 3\text{ m}$ long) which are instrumented for charge division in order to determine a space point. During the next run, two drift tubes will be ganged together for readout purposes limiting the z resolution to $\sim 6\text{ mm}$. Upgrading the readout would improve the z resolution to $\sim 3\text{ mm}$.

Forward Tracking Chamber (FTC)

The FTC is a radial wire chamber that measures the ϕ coordinate of particles from $2^\circ < \theta < 10^\circ$ that pass through the hole in the endplug. The chamber is divided into 72 ϕ cells that are 21 wires deep in z and have a 2° tilt with respect to the z axis for resolving left-right ambiguities; the cell size is $\Delta\phi = 5^\circ$. The chamber is read out with multihit TDCs and has a single hit precision of $\sim 125\mu/\text{wire}$ and double hit resolution of $\sim 4\text{mm}$. A few wires in each ϕ cell will be instrumented for charge division and be read out with an FADC.

Muon Detection System

Behind the central and forward calorimetry are muon detectors. The central muon detector is four planes of large drift tubes operated at high gain in order to enhance the charge division measurement used to determine the third coordinate. They cover an angular range from $50^\circ < \theta < 90^\circ$. In the forward direction the muon detector consists of two magnetized steel toroids between three sets of drift chambers. The expected momentum resolution is $\Delta P/P \sim 20\%$. The forward muon detector covers the angular region between $2^\circ < \theta < 17^\circ$. Upgrades to the muon detection that would increase the angular coverage are being considered.

4 Data Acquisition System

The general data acquisition system is FASTBUS based and there are two distinct types of front end electronics that feed this system. One type sits on the detector in RABBIT (Redundant Analog Bus Based Information Transfer) crates which have a backplane with an analog bus. The data in the individual RABBIT modules is converted into a voltage and stored on capacitors. These voltages are multiplexed over the analog bus and digitized by a precision 16 bit ADC (allowing a large dynamic range) which sits in a special slot in the RABBIT crate.

The other type of front end electronics consists of pulse amplification and shaping on the detector followed by digitizing modules residing in FASTBUS crates (digital bus) located in the counting room. Currently this scheme is used for multihit TDCs and FADCs.

In order to control the data acquisition system and move the data into the computer, four complicated modules are required. These multiported, intelligent devices are all new and the fall 1985 run was an important test of them under actual running conditions.

- UPI (Unibus Processor Interface): Interfaces the computer to FASTBUS.
- SI (Segment Interconnect): Networks the FASTBUS crates.
- MX/MEP: Interfaces the RABBIT system to FASTBUS. Controls the ADCs, stores pedestals, buffers the data, and does calibrations.
- SSP (SLAC Scanner Processor): Reads FASTBUS front end modules, buffers and formats the data, and does calibrations.

5 Trigger

The trigger is divided into three levels. Level 1 was the only one implemented for the fall 1985 test run.

Level 1

The level 1 trigger decision is made between beam crossings (i.e. less than $\sim 3\frac{1}{2}\mu\text{sec}$) and therefore introduces no deadtime. The goal of level 1 is to reduce the trigger rate to less than $\sim 5000 \text{ events/sec}$ in order to limit the deadtime due to level 2. The ingredients of level 1 can include the following:

- Calorimetry. Channels are added and weighted (usually with $\sin\theta$ and any necessary calibration constants) to form trigger towers. The electromagnetic and hadronic energy are kept separate and there is no clustering. Up to four thresholds are defined and energy sums are made for towers above the different thresholds. Each sum can then be compared to a sum threshold. The calorimetry was used for the fall 1985 run with the requirement of at least one tower above $\sim 2 \text{ GeV}$.
- Trigger Counters. Hits in both banks of hodoscopes are required with proper timing for a beam-beam interaction. Vetoes can be made on events that have out-of-time hits in hodoscope elements. The trigger counters were used for the fall 1985 run with the requirement that at least one counter in each direction have a hit within a loose timing window.
- Muon Detectors. Fast signals from both the central and forward muon detectors are available (not implemented for 1985 test run).
- Central Tracking Detector. At least one stiff track in the central tracking detector can be required (not implemented for 1985 test run).

Level 2

The level 2 decision typically takes about $10\ \mu\text{sec}$ —sometimes longer for interesting events. During this time, the detector is dead and the data in the front end electronics is held on sample-and-hold capacitors or in shift registers awaiting the decision on whether the event will be encoded. The hardware is designed to handle $\sim 100\ \text{events/sec}$ satisfying level 2. Level 2 was not used in the fall 1985 test run but should be ready this year. Some items planned for level 2 are:

- Calorimetry. Clusters can be done for both electromagnetic and electromagnetic plus hadronic energies. Triggers for jets and missing transverse energy are also possible.
- Tracking. High momentum tracks will be available from the central tracking chamber. These can be correlated with energy clusters and muon detector segments to form electron and muon signals.

Level 3

The level 3 trigger is a microprocessor based system that has access to all the data in the event and can do at least partial event reconstruction. A computer "farm" of approximately 100 microprocessors running in parallel is planned with each microprocessor working on a different event. Each processor will have about one second for each event if the rate of events passing level 2 is $\sim 100\ \text{events/sec}$. Level 3 is needed at full luminosity in order to reduce the rate of events written to tape to a few per second. Tests of level 3 will be made during the next run.

6 Results of the Fall 1985 Test Run

The results of the test run can be divided into two categories: first, the experience gained with the hardware and software necessary for doing colliding beam physics and second, the actual events themselves.

Experience with the Detector and other Components

As expected, the benefits of bringing up and exercising such a complicated system were substantial. Some of the major points can be summarized as follows:

- Data Acquisition System. A system with all the major components was demonstrated to work under actual running conditions. All of the complicated new modules mentioned earlier worked together along with the supporting software.
- Level 1 Trigger. The basic hardware all worked and the calorimetry information seen by level 1 was essentially the same as that encoded by the data acquisition system. Energy levels could be set to $\sim 1\ \text{GeV}$.

- **Detector Components.** The central and endwall calorimeters, the central muon detectors, the VTPC, and the trigger counters all worked and data was written to tape from these detectors.
- **Calorimetry Calibration.** The calibration systems for the central and endwall calorimeters were demonstrated to have worked. Energy response was tracked to $\sim 1\%$.
- **Forward Silicon Strip Detectors.** Prototypes were demonstrated to work very close to the beam ($\sim 6\text{ mm}$ from beam) with low rates in the detector. Electronic noise was also demonstrated not to be a problem.
- **Accelerator and Antiproton Source.** All the important pieces of the antiproton source worked and the Tevatron was demonstrated to work as a collider. The luminosity was low, but as a result of the run, most of the problems are understood and much higher luminosity is expected for the next run.

Events

Collisions at a center of mass energy of 1.6 TeV were seen from three different shots of antiprotons. Typical conditions were $\sim 10^{10}$ protons mostly in one bunch and $\sim 10^7$ antiprotons in several bunches giving a luminosity in the range of $10^{23} - 10^{24}\text{ cm}^{-2}\text{sec}^{-1}$. The level 1 trigger required a trigger tower with more than $\sim 2\text{ GeV}$ and a particle in the trigger counter hodoscopes in both directions. This trigger was expected to see 2-5 mb of cross section. Roughly the expected number of events were observed and their multiplicity and energy distributions were reasonable.

The result of $\sim 3\text{ hours}$ of running was ~ 280 triggers and 23 definite beam-beam interactions inside the VTPC active region plus a couple of possible events. All 23 good events were found independently by the following three methods:

- **Hand scan of the VTPC data.** Physicists visually scanned the VTPC displays looking for good events. Two displays for good events are shown in figures 8 and 9. All 23 good events plus ~ 3 additional candidates were found.
- **Computer scan of the VTPC data.** All the track segments with more than 7 wires in a single VTPC octant were projected onto the beam axis. A five centimeter wide window was moved along the beam axis to find the point of maximum clustering of z intercepts. A good event was defined as having six or more segments pointing at the window with an asymmetry $|(N_f - N_b)/(N_f + N_b)| \leq 0.6$. Only the 23 good events were found.
- **Computer scan of the trigger counter data.** At least 3/8 of the channels in both the proton and antiproton direction were required to have a hit within $\sim 5\text{ nsec}$ of the proper time. All 23 good events were found plus one possible event that was also found by hand scanning. By looking in a wider timing window, there was evidence of nine other beam-beam interactions due to satellite beam bunches

occurring outside the VTPC active region. This number is consistent with the predicted decrease in luminosity for interactions away from the detector center.

In the VTPC event displays shown in figures 8 and 9, the upper four octants are superimposed at the top and the lower four octants at the bottom. Note that in these displays the aspect ratio is distorted by a factor of 4 (i.e. an apparent angle of 40° with respect to the beam is really $\sim 10^\circ$). Also two half-modules on the right side were dead due to high voltage problems.

During the test run, there was a relatively thick stainless steel beam pipe which led to a considerable number of soft secondaries in the VTPC. Changing to a thin beryllium beam pipe should cause more than an order of magnitude reduction in the number of secondaries seen in the VTPC during the next run.

In addition to the data from the VTPC and trigger counters, some energy was always seen in the calorimetry because of the level 1 trigger requirements. Figure 10 shows a lego plot of the calorimetry for the event with the biggest energy deposition—a cluster of energy greater than 10 GeV. This is the same event as shown in the VTPC display in figure 9.

7 Future Plans

The current plans call for the next run to start about December 1, 1986. This will still be a test run for the antiproton source. It will also be a commissioning run for the full CDF detector. The initial luminosity will be low with one bunch operation. The goal is to achieve 3 bunch operation with a luminosity of $10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$ by the end of the run. The run is expected to last about 3 months.

CDF expects to have an integrated luminosity of the order of 100 nb^{-1} during this run. With 100 nb^{-1} CDF should see a few hundred W's going to charged lepton plus neutrino, roughly twenty Z's decaying to charged lepton pairs, and a few W's decaying to top which then decays to beauty. There should also be 100,000 jets with $P_t \geq 50 \text{ GeV}$ and 200 jets with $P_t \geq 200 \text{ GeV}$. When looking for compositeness, $\Lambda = 0.75 \text{ TeV}$ changes the cross section at $P_t = 200 \text{ GeV}$ by a factor of two.

At the end of the next run there will be a fixed target run of approximately 5 months. The plan is then to alternate collider and fixed target running with about equal time for each. There are no long shutdowns planned for construction.

8 Conclusion

CDF will take data in the near future with a center of mass energy of 1.6 to 2.0 TeV and good luminosity. The detector covers a very large solid angle with good calorimetry and tracking. The projective tower structure of the calorimetry with both good energy resolution and good spatial segmentation should make the detector extremely powerful in answering questions that are inaccessible at lower energies. The detector construction and antiproton source development are on a schedule which should yield physics results from the winter 1986-1987 run.

Appendix A: CDF Collaboration

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Figure Captions

- Figure 1. An isometric view of the CDF detector.
- Figure 2. A vertical cut through one-half of the CDF detector.
- Figure 3. Installation of the superconducting solenoid between the central detector endwalls.
- Figure 4. Table summarizing the calorimetry.
- Figure 5. The central detector moving out of the assembly area toward the collision hall in preparation for the 1985 test run. The outside of two central calorimetry arches with along with their cabling and RABBIT crates can be seen. The cable carrier is above the detector.
- Figure 6. An isometric view of two VTPC modules. They are rotated in ϕ by 11.3° with respect to each other.
- Figure 7. VTPC modules being installed inside the central detector for the fall 1985 run.
- Figure 8. Event display of the VTPC wire data for a good beam-beam interaction (fall 1985 test run). The ϕ projection of the calorimetry is also shown. Note that the aspect ratio is distorted.
- Figure 9. Event display of the VTPC wire data for the beam-beam interaction with the most energy in the calorimetry (fall 1985 test run). Note that the aspect ratio is distorted.
- Figure 10. Central calorimetry lego plot for the event shown in figure 9. The electromagnetic contribution is shown with lighter shading.

• Figure 1. An isometric view of the CDF detector.

• Figure 2. A vertical cut through one-half of the CDF detector.

• Figure 3. Installation of the superconducting solenoid between the central detector endwalls.

EM Calorimetry Summary

	<u>Forward</u>		<u>End Plug</u>		<u>Central</u>
Ang. Range	2° to 10°		10° to 37°		37° to 90°
Towers in η	18		16		10
Tower Size	$\Delta\eta \sim 0.1$ $\Delta\phi = 5^\circ$		$.05 < \Delta\eta < 0.1$ $\Delta\phi = 5^\circ$		$.087 < \Delta\eta < .13$ $\Delta\phi = 15^\circ$
Construction	Pb-gas tubes		Pb-gas tubes		Pb-scintillator
R.L. per Layer	$.9X_0$		$.53X_0$		$.6X_0$
Layers	15	15	5	24	5
R.L. per Sect.	$13X_0$	$13X_0$	$2.7X_0$	$13X_0$	$2.7X_0$
$\Delta E/E$	$\sim 27\%/\sqrt{E}$		$\sim 24\%/\sqrt{E}$		$\sim 14\%/\sqrt{E}$
Position Resol.	2-4 mm		1-2 mm		1.5-3 mm

Hadron Calorimetry Summary

	<u>Forward</u>	<u>End Plug</u>	<u>End Wall</u>	<u>Central</u>
Ang. Range	2° to 10°	10° to 30°	30° to 45°	45° to 90°
Tower Size	$\Delta\eta = 0.1$ $\Delta\phi = 5^\circ$	$\Delta\eta = .09$ $\Delta\phi = 5^\circ$	$.08 < \Delta\eta < .12$ $\Delta\phi = 15^\circ$	$.1 < \Delta\eta < .15$ $\Delta\phi = 15^\circ$
Construction	2 in. Fe + gas tubes	2 in. Fe + gas tubes	2 in. Fe + scintillator	1 in. Fe + scintillator
Layers	28	20	15	32
$\Delta E/E$	$\sim 125\%/\sqrt{E}$	$\sim 14\%$ at 50 Gev	$\sim 14\%$ at 50 Gev	$\sim 70\%/\sqrt{E}$

• Figure 4. Table summarizing the calorimetry.

- Figure 5. The central detector moving out of the assembly area toward the collision hall in preparation for the 1985 test run. The outside of two central calorimetry arches with along with their cabling and RABBIT crates can be seen. The cable carrier is above the detector.

• Figure 6. An isometric view of two VTPC modules. They are rotated in ϕ by 11.3° with respect to each other.

• Figure 7. VTPC modules being installed inside the central detector for the fall 1985 run.

Max energy = 2.4 GeV

- Figure 8. Event display of the VTPC wire data for a good beam-beam interaction (fall 1985 test run). The ϕ projection of the calorimetry is also shown. Note that the aspect ratio is distorted.

- Figure 9. Event display of the VTPC wire data for the beam-beam interaction with the most energy in the calorimetry (fall 1985 test run). Note that the aspect ratio is distorted.

E_{tot} = 2.7 GeV
 Date = 10/10/80
 Display of Raw Data

• Figure 10. Central calorimetry lego plot for the event shown in figure 9. The electromagnetic contribution is shown with lighter shading.

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