STATUS OF THE TEVATRON

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1. INTRODUCTION

The start up of the Tevatron for colliding beams physics began in January. The center of mass energy was set at 1800 GeV and no difficulties were encountered in achieving and sustaining that energy. While the peak luminosity was a very modest 10^{26} cm^{-2} sec^{-1} in the beginning it increased steadily as operating experience was gained. By the beginning of February three bunches of protons were colliding with three bunches of antiprotons on a routine basis. After some initial difficulties, which were part of the learning experience, more than eighty percent of the attempted stores provided luminosity of at least a few hours duration. In March the CDF detector began to record events routinely and the peak luminosity reached 10^{28} cm^{-2} sec^{-1}. In April our initial goal of 10^{29} cm^{-2} sec^{-1} was exceeded. During the last two weeks of the run 2 nb^{-1} per day were delivered to BØ, the location of CDF. The collider was sufficiently stable to allow CDF to log 25 nb^{-1} of data on tape. Three other experiments managed to debug their partially built apparatus and in some instances take data simultaneously with CDF.

2. TEVATRON COLLIDER PERFORMANCE 1987

Table 1 summarizes the essential data which describes the performance of the Tevatron Collider during the 1987 run.

Table 1: Tevatron Collider Performance 1987

Center of mass energy	1800 GeV
Peak luminosity	1.2×10^{29} cm^{-2} sec^{-1}
Initial luminosity lifetime	8 hours
Number of stores attempted	116
Number of stores (% success)	92 (80%)
Number of stores ended by failures (% failures)	47 (51%)
Integrated luminosity (delivered at BØ)	55 nb^{-1}

The values of peak luminosity and integrated luminosity quoted in this report have an uncertainty of 40% and are consistent with measurements of

the machine parameters; bunch currents, bunch lengths, and $\beta*$. CDF estimated 70 nb^{-1} for the same period on the basis of counting rates in their trigger counters and an assumed but reasonable total cross section of 77 mb.

More detailed numbers showing how the peak luminosity was achieved are contained in Table 2. The design parameters of the Tevatron collider corresponding to these values are also shown for comparison.[1]

Table 2: Factors determining the luminosity in 1987

	Achieved: 1987	Design Goals: 1982
Number of p and $\bar{p}$ bunches	3	3
Peak number of p's/bunch	9×10^{10}	6×10^{10}
Peak number of $\bar{p}$'s/bunch	10^{10}	6×10^{10}
$\beta*$ at the B0 collision point	85 cm	100 cm
Bunch length p's ($\bar{p}$'s)	55 (60) cm	40 (40) cm
Initial p transverse emittance (normalized)	25π mm-mr	24π mm-mr
Initial $\bar{p}$ transverse emittance (normalized)	35π mm-mr	24π mm-mr
Longitudinal emittance p ($\bar{p}$)	3.6 (5.0) ev-sec	3.0 (3.0) ev-sec
Peak luminosity	$1.2\times10^{29}cm^{-2}sec^{-1}$	$10^{30}cm^{-2}sec^{-1}$

The peak luminosity was less than the design value primarily because the number of antiprotons/bunch was a factor six below the design goal of 6×10^{10}/bunch. The larger than design transverse emittances and longitudinal emittance of the antiproton beam also caused the luminosity to fall below the design value. The larger than design longitudinal emittance contributed to the reduction in luminosity in two ways. First, the larger momentum spread caused a growth in the transverse emittance when the antiprotons were transferred from the Main Ring to the Tevatron. Second, the bunch lengths were comparable to $\beta*$ and thus β was significantly larger than $\beta*$ over part of the interaction volume. The second effect lead to a reduction in the luminosity by a factor of 1.4.

3. FACTORS WHICH LIMITED COLLIDER PERFORMANCE IN 1987

To understand why the antiproton bunch intensity was only 10^{10}/bunch it is instructive to review the steps which lead to a dense bunch of antiprotons in the Tevatron at low β. To assist the reader in following these steps a schematic drawing of the accelerator complex is shown in Figure 1. Both protons and antiprotons were transferred from their respective sources, the Booster and Accumulator to the Main Ring, at 8.9 GeV (total energy). Antiprotons and protons are separately accelerated from 8.9 GeV to 150 GeV in the Main Ring and then transferred to the Tevatron. Since the transition energy of the Main Ring is 17 GeV both species must go through transition. The maximum longitudinal emittance of a single 53 MHz bunch that can be accelerated efficiently through transition is about .2 ev-sec. If a single bunch of 6×10^{10} antiprotons were to be extracted from the Accumulator it would have a longitudinal emittance of at least 1.5 ev-sec. The transition problem is avoided by accelerating the 6×10^{10} antiprotons as a train of roughly 10 adjacent bunches. Since each bunch has a longitudinal emittance of less than .2 ev-sec the antiprotons can traverse transition without loss. The train of bunches is coalesced into a single bunch in the

Main Ring after it has been accelerated to 150 GeV. After coalescing, the single bunch of antiprotons is transferred to the Tevatron.

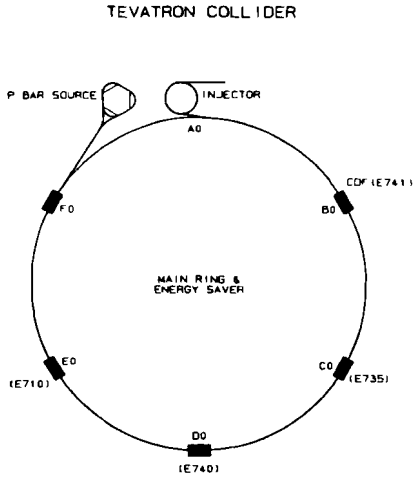

Fig. 1 A schematic representation of the Fermilab Collider and the accelerators which create the proton and antiproton beams. The numbers in parenthesis designate colliding beam experiments.

Calculations of the bunch coalescing process predicted a longitudinal emittance growth of somewhat less than a factor of 2. The actual emittance was considerably larger than the expected 3 eV-sec as noted in Table 2. The causes of this growth are partially understood.

In practice the three bunches of protons are formed first and then the three antiproton bunches are formed. Typically eight bunches of protons are extracted from the Booster, accelerated to 150 GeV and then coalesced. Since the antiprotons in the Accumulator are not as dense as the protons in the Booster, 12 bunches of antiprotons are needed to form a coalesced bunch.

Under the best of circumstances only 60% of the antiprotons were captured in a single bunch. 20% of the remaining antiprotons were captured in the two adjacent satellite bunches (10% in each bunch) and the rest of the antiprotons were not captured at all. Because fewer bunches of protons needed to be coalesced protons were coalesced somewhat more efficiently.

Once the ensemble of three bunches of protons and three bunches of antiprotons were circulating in the Tevatron they were accelerated to 900 GeV/beam. At the start of acceleration some pbars were lost because the bucket area was reduced. Upon reaching 900 GeV the low β insertion was energised.

The efficiency of each of these steps is shown in Table 3. The overall efficiency for antiprotons was between 25 and 30%. When the bunch coalescing was at its best the transfer efficiency reached 34%. Clearly there is room for improvement.

Table 3: Summary of Transfer Efficiencies

	$\bar{p}$	p
Accumulator (Booster) to Main Ring	80%	80%
Acceleration to 150 GeV	90%	100%
Bunch coalescing	60%	75%
Main Ring to Tevatron	75%	85%
Acceleration to 900 GeV*	100%*	100%
Low β squeeze*	90%*	100%
Overall - typical	30%	51%
Max particles/bunch transferred	10^{10}	9×10^{10}

*$\bar{p}$ transverse emittance grew from 25π mm-mr to 35π mm-mr during these steps.

The bunch coalescing process was one of the main reasons for the low efficiency since it lead to the larger than expected momentum spread and bunch length. The larger momentum spread lead in turn to a dilution of the transverse emittance when the antiprotons were transferred from the Main Ring to the Tevatron. This happened because the relatively large vertical dispersion of the Main Ring at EØ was not matched to the zero vertical dispersion of the Tevatron at EØ. The Main Ring overpass which was built to guide the Main Ring beam around the most sensitive parts of the DØ detector, was the main cause of the large vertical dispersion mismatch. The dispersion mismatch caused a doubling of the transverse emittance of the pbars and the protons from 12π mm-mr to 25π mm-mr.

The greater fractional loss of antiprotons and the greater transverse emittance growth of the antiprotons in the Tevatron were due in part to the beam-beam tune shift. The beam-beam tune shift of the antiprotons caused by the protons was typically ten times greater than the beam-beam tune shift of the protons caused by the antiprotons because of the differences in the bunch currents. The difference in beam-beam tune shifts caused the antiprotons to be much closer to dangerous betatron tune resonances than the protons. The control of the tune during acceleration and the low beta squeeze was not sufficiently precise to keep the antiprotons away from such resonances. Once the beams had stabilized at low beta the beam-beam tune shift did not appear to cause further problems.

The transverse emittances of both beams grew slowly, thereby limiting the luminosity lifetime to eight hours. Since a considerably longer luminosity lifetime is expected for these bunch intensities and emittances, it is believed that the emittance growth is due to one or more noise sources. The sources have not been identified at this time. It is worth noting that the beam intensity lifetime was much longer than eight hours. Since we have no reason to believe that any of these problems are fundamental, we expect to make significant improvements in the transfer efficiency and luminosity lifetime over the next two years.

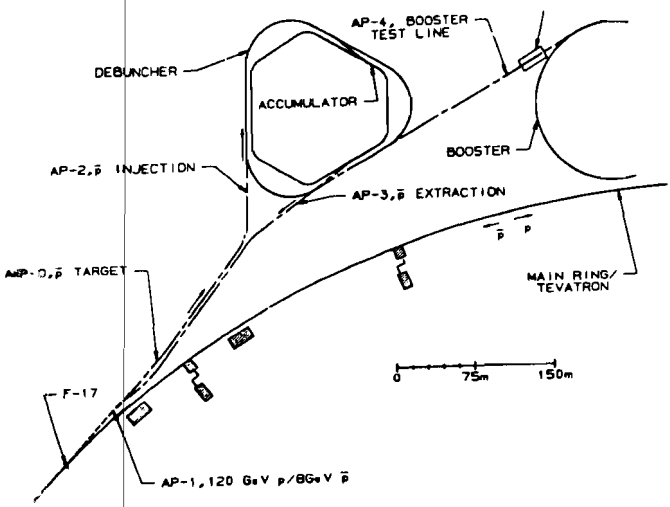

Fig. 2 Schematic of the antiproton source and the related accelerators and beam transport lines used for pbar production.

The performance of the Pbar Source was just as impressive as the Tevatron. A schematic diagram of the Pbar Source is shown in Figure 2. A summary of the performance of each of these steps is given in Table 4.

Table 4: Pbar Source Performance 1987

	Achieved: 1987	Design Goals: 1982
Antiprotons produced in the Debuncher acceptance per Main Ring cycle	1.2×10^7	7×10^7
Number of Main Ring cycles/hour	1400	1800
Efficiency of Debuncher transfer to Accumulator	80%	100%
Efficiency of antiproton stacking	90%	85%
Peak stacking rate (p̄/hr)	1.2×10^{10}	10×10^{10}
Maximum stack intensity	39×10^{10}	40×10^{10}
Normalized transverse emittance of p̄'s in the core (mm-mr)	10π	20π
RMS energy spread of p̄'s in the core	2.0 mev	1.6 mev

The major differences between the realized performance and the design goals can be attributed to the following: a smaller than expected cross section for pbar production on tungsten and the flux of 120 GeV protons which was delivered to the target. On the basis of the measurements of the pbar flux emerging from the tungsten target we have concluded that the cross section for pbar production at $x_f=0$ is probably a factor of 2.5 smaller than we expected. Unlike other factors, there is nothing that can be done to increase it. On the other hand the acceptance of the pbar transport line and the Debuncher can be increased to accept more antiprotons.

The Main Ring proton intensity was typically 1.3×10^{12} protons/pulse whereas the design anticipated 2.0×10^{12}/pulse. The Main Ring cycle rate was 1400 pulse/hour and the design anticipated 1800 pulses/hour. The Main Ring cycle rate and intensity are expected to reach or exceed the design performance by 1988.

All of the multigigahertz, high power cooling systems performed very well. The fact that the normalized transverse emittance of the core was only 10π mm-mr is a tribute to the good performance of the cooling systems. With the planned improvements to the Main Ring the stacking rate should reach 2.5×10^{10}/hour in time for the 1988 collider run. The increased rate should allow stack intensities of 60×10^{10} antiprotons.

Our goal for 1988 is to accumulate an integrated luminosity of 500 nb^{-1}. We expect to at least double the peak luminosity. A doubling of the pbar transfer efficiency and an increase in the number of pbars taken from the Accumulator per transfer by a factor of two will increase the number of antiprotons in thee Tevatron by a factor of four. The prospects for achieving such a factor of four improvement in the peak luminosity are reasonable. Our goal for 1989 and subsequent years is to double the integrated luminosity/crossing every year.

4. THE TEVATRON COLLIDER PHYSICS PROGRAM

During the 1987 collider run four experiments reached the data taking stage. Table 5 provides a listing of the currently approved experimental program. Except for E740, the DØ collaboration, all of the experiments obtained data. DØ is expected to have a check out run in 1989 and be ready for luminosity in 1990.

Table 5: Tevatron Collider Experimental Program

Experiment Number	Subject	Location
E710	Elastic Scattering & total cross section	EØ
E713*	Search for monopoles & & other heavily ionising particles	DØ
E735	Search for evidence of a quark-gluon plasma phase transition	CØ
E740+ - "DØ"	Physics at the electroweak scale	DØ
E741 - "CDF"	Physics at the electroweak scale	BØ

*Completed during the 1986-1987 running period.
+After 1988 the DØ straight section will be used by E740, "DØ".

Only BØ has a low β insertion, $\beta*$ at the other locations was between 80 and 150 m. We expect to install a second low β insertion at DØ in 1989.

5. E710 ELASTIC SCATTERING

The goals of E710 are to measure $\bar{p}p$ elastic scattering and total cross sections between $\sqrt{s}$=300 and 2000 GeV. The participating institutions are Bologna, Cornell, Fermilab, George Mason, Maryland and Northwestern.

Detectors for elastic scattering are located in four sets of dual "Roman Pots" placed above and below the circulating proton and antiproton beams on either side of the EØ straight section. Each pot contains three scintillation counters, for triggering, and a drift chamber which give four vertical drift (scattering angle) coordinates and four horizontal charge division coordinates. Typical accuracies achieved are about ±0.1 mm and ±0.6 mm respectively for the two coordinates. Two of the four sets of pots are located about 100 m on either side of the interaction point. Once the beams are at 900 GeV and the low beta insertion is fully energised, the drift chambers and counters can be brought within 5 mm of the beams.

The collision point is surrounded by 48 scintillation counters and six sets of drift chambers. These are used to detect inelastic interactions. By using the optical theorem the total cross section and elastic cross section can be obtained from these measurements in a luminosity independent manner.

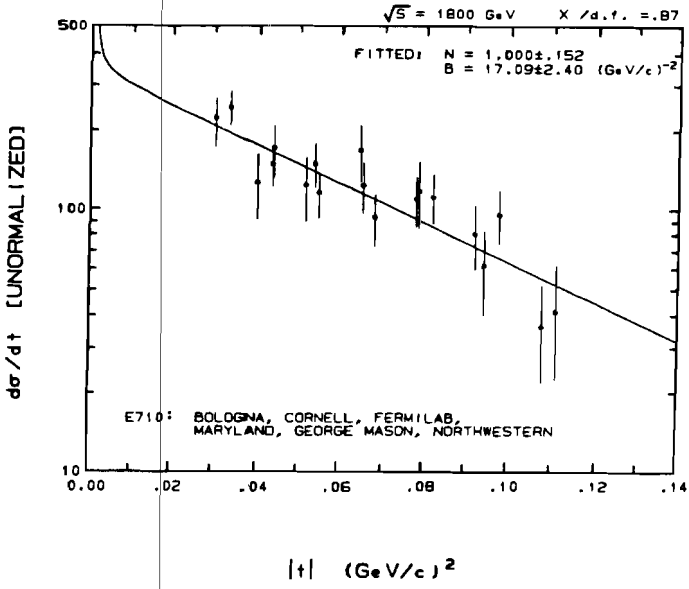

Fig. 3 Preliminary t distribution for $\bar{p}p$ elastic scattering from E710.

Track chambers located outside of the calorimeter are used to measure the direction of penetrating charged particles, such as muons. Downstream of the forward and backward calorimeters, magnetized iron toroids and track chambers are placed to detect muons. Details of the performance of the muon detectors can be found in a contribution to these proceedings.[5]

All elements of the detector were successfully used during the run. The power of CDF can be sensed from the discussion of three individual events which represent three of the major classes of events which CDF was designed to detect. The energy scale of these events is uncalibrated and the events have only been subjected to a very preliminary analysis. The first event is the two jet event with the largest amount of E_T observed and analyzed thus far. Figure 4 shows the traditional lego plot of a two jet event which deposited 865 GeV of energy in the calorimeter.

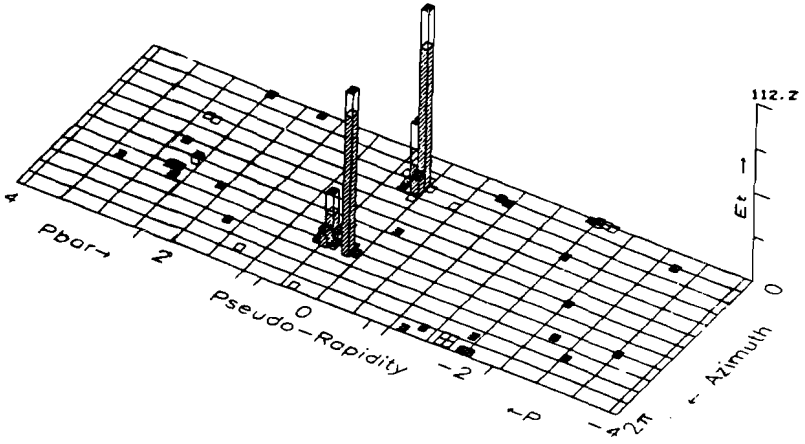

Fig. 4 A multi-jet event observed in the CDF detector. The shaded volume represents deposition of energy in the hadron calorimeter and the unshaded volume represents energy deposited in the electromagnetic calorimeter.

The jet at pseudo-rapidity of +.15 and azimuth of 71° has a transverse energy of 180 GeV. The jet at pseudo-rapidity of .38 and azimuth of 242° has a transverse energy of 163 GeV. There is a third jet with a transverse energy of 22 GeV at pseudo rapidity of -2.0 and azimuth of 355°. The total E_T for the event is 415 GeV. A preliminary analysis of the jet events can be found elsewhere in these proceedings.[3]

The second event is an example of a W candidate. The lego plot is shown in Figure 5.

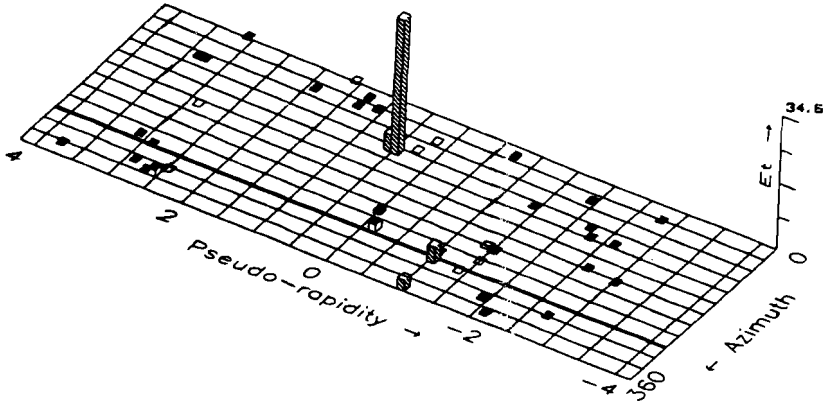

Fig. 5 A W candidate observed in the CDF detector. The shaded volume represents energy deposited in electromagnetic calorimeters. The opaque volume represents energy deposited in hadron calorimeters.

The energy deposited in the tower at pseudo rapidity of 0 and azimuth 270° is 34.6 GeV. In the adjacent tower another 8 GeV of energy was deposited. The transverse energy of this purely electromagnetic jet was 42.2 GeV and its total energy was 47 GeV. A missing transverse energy of 39 GeV is needed to balance the observed energy deposited in the calorimeter. The missing E_T is suggestive of a neutrino. The analysis of the charged tracks observed in the central tracking chamber shows that the most energetic track, with a reconstructed momentum of 46.8 GeV/c points at the calorimeter tower containing the 34.6 GeV electromagnetic shower. Since the tracking chamber momentum measurement is in very good agreement with the calorimeter energy measurement, the event has the classical features of a W.

E710 took data during the recent $\sqrt{s}$=1800 GeV collider run, and an analysis of that data is currently underway. Figure 3 shows the distribution of elastically scattered events recorded in a few hours of running. The slope of the t distribution obtained from this data was 17.1 ± 2.4 $(GeV/c)^{-2}$. It is consistent with extrapolations from previous experiments. During the run elastic scattering measurements were made between $|t|$ = .01 and .12.

6. E735: DUKE, FERMILAB, IOWA STATE, NOTRE DAME, LLL, PURDUE, WISCONSIN

The goal of the experiment is to determine whether or not an observable quark gluon plasma is created in $\bar{p}p$ collisions at $\sqrt{s}$ = 1800 GeV.[2] The experiment will measure the charged particle multiplicity in the central region and the momentum spectrum of particles produced in the central region. A second phase of the experiment will measure the γ ray multiplicity.

Charged particles with a pseudo-rapidity magnitude of less than 3 were detected with counters and end cap drift chambers. A cylindrical drift chamber capable of handling high multiplicities will be installed for the 1988 run. When the cylindrical drift chamber is installed it will be possible to detect and measure up to 120 tracks in an event containing up to 200 charged particles if the tracks are distributed uniformally in pseudo-rapidity over the full kinematic range. Since this chamber is not immersed in a magnetic field the momenta of the charged particle tracks is not measured.

A magnetic spectrometer, with an acceptance of 20° in azimuth and 1.35 units of pseudo-rapidity, was used to measure the momenta of roughly one charged particle per recorded event. The particle traversing the magnetic spectrometer was identified means of time of flight. This allowed π, k, p separation up to about 1 GeV/c. Since β^* at CØ was about 75 m the luminosity was roughly 100 times smaller than the luminosities noted in Table 1. Such a luminosity is compatible with the experimenters needs.

7. COLLIDER DETECTOR AT FERMILAB (CDF)

CDF is a large general purpose detector designed to explore the electroweak scale and beyond. The collaborating institutions are: Argonne, Brandeis, Chicago, Fermilab, Frascati (INFN), Harvard, Illinois, KEK, LBL, Pennsylvania, Pisa (INFN), Purdue, Rockerfeller, Rutgers, Texas A&M, Tsuuba, and Wisconsin.

The central detector consists of a 3m diameter, 1.5T solenoid filled with track chambers. Charged particle momenta can be measured to an accuracy of $(.002p^2)$, where p is the particle momentum in GeV/c. The solenoid is surrounded by a set of segmented calorimeters. The central calorimeter, the end wall calorimeters, and the end plug calorimeters nestle together as part of the movable portion of the detector. The separately installed forward and backward calorimeters complete the array. A more detailed description of the CDF calorimeter is contained in other contributions to these proceedings[3] and in earlier publications.[4]

The calorimeter cells are separated into an electromagnetic section and a hadronic section in order to distinguish electrons from charged hadrons. Test beam measurements have shown that single hadrons can be rejected by a factor of 300 to 1000 when only a single charged particle traverses a calorimeter cell.[4]

Figure 6 shows an example of a Z° candidate. Two energetic electromagnetic showers of 53 GeV and 30 GeV are seen in the calorimeter.

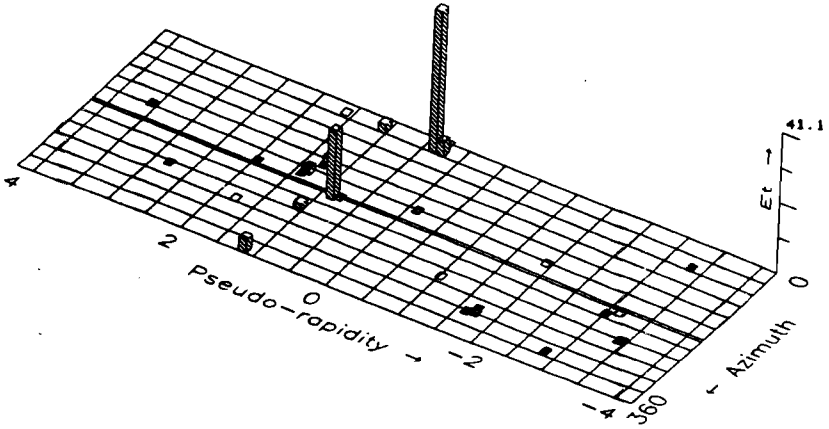

Fig. 6 A Z^{o} candidate observed in the CDF detector. The shaded volume represents energy deposited in electromagnetic calorimeters. The opaque volume represents energy deposited in hadron calorimeters.

There is very little activity in the other calorimeter towers. An analysis of the charged tracks in the central tracking chamber yields two very stiff energetic tracks of opposite sign with momenta of 50 and 42 GeV/c respectively. The somewhat low value of energy deposited in the calorimeter can be explained by the fact that the 42 GeV/c track points at the boundary between the central calorimeter and end wall calorimeter. A preliminary analysis of the W and Z candidates can be found elsewhere in these proceedings. [5]

8. DØ DETECTOR

The construction of the DØ detector is in progress.[6] An artist's sketch of the detector is shown in Figure 7.

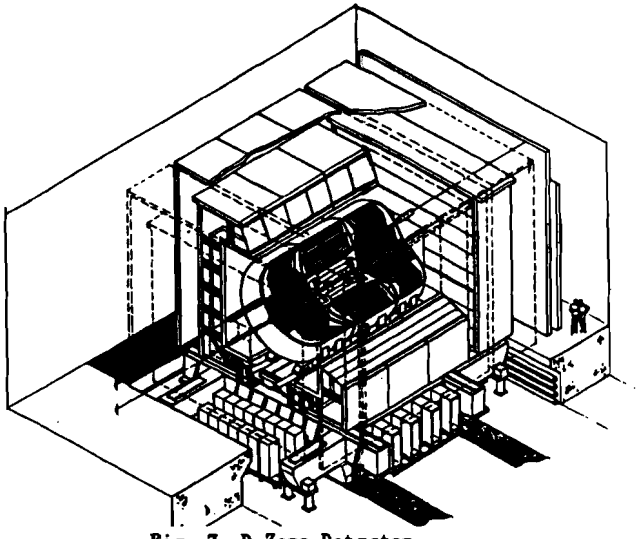

Fig. 7 D-Zero Detector

The beam pipe is surrounded by track chambers which are not immersed in a magnetic field. This is an important difference between DØ and CDF. The DØ calorimeter which surrounds the track chambers consists of three segmented ionization sampling calorimeters. The central calorimeter is made "hermetic" by two endcap calorimeters as shown in Figure 7. The sampling medium is liquid argon and the radiator consists primarily of uranium plates.

The 7 interaction lengths of the calorimeter makes an excellent muon filter. To take advantage of that circumstance the calorimeter is surrounded by magnetised steel and track chambers. The track chambers are located between the calorimeter and the magnetized steel and outside of the magnetised steel. They are used to measure the direction and momentum of each penetrating particle. The DØ detector uses a set of transition radiation detectors (TRD) interspersed with the tracking chambers to identify electrons in a cluster of hadrons.[6]

The construction of DØ is proceeding rapidly. The partially completed detector will be installed in DØ in 1989. The detector should be completed in time for the 1990 collider run.

9. EXPECTATIONS FOR THE LONG TERM IMPROVEMENTS IN THE TEVATRON AND PBAR SOURCE

The preceding material gives a sense of what can be accomplished with the Tevatron in the next few years. In particular, it should be possible to reach the design luminosity of 10^{30} cm^{-2} sec^{-1} during the 1989 run. With a

peak luminosity of 10^{30} cm^{-2} sec^{-1} it should be possible to obtain an integrated luminosity of 2 pb^{-1}/collider run. Such an integrated luminosity can extend our knowledge of the electroweak interactions and QCD to mass scales of 300 GeV/c^2 and 500 GeV/c^2 respectively. The scientific potential of the Tevatron will not have been exhausted at that point. By extending the luminosity by an order of magnitude to 10^{31} cm^{-2} sec^{-1} these limits can be extended by nearly a factor of two.

It should be possible to increase the luminosity somewhat beyond 10^{31} cm^{-2} sec^{-1}. To do this we are planning major changes to the Linac, Pbar Source, Main Ring and Tevatron. The most significant change will be the introduction of electrostatic beam separators so that the beams only collide at a few places. To increase the luminosity by a factor ten or more the number of bunches will have to be increased by the same factor. Working with such a large number of bunches is an extraordinary challenge.

Let me conclude by saying that we expect that the Tevatron will have a useful life for physics into the mid-nineties. I expect that audiencies such as this will be treated to a delightful menu of new bosons, heavy quarks, and perhaps some exotic particles emerging from collisions in the Tevatron in the not too distant future.

ACKNOWLEDGEMENTS

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