The 1987 TEVATRON Collider Run in Retrospect *

John L. Crawford and David A. Finley

Operation of the First 1.8-TeV Collider Run

Overview

This first TEVATRON Collider run at 1.8 TeV had exceeded, or very nearly met, all of its goals by the end of April 1987. This is shown in Table I which summarizes the history and goals of the TeV I project. The progress made since the very first use of the Collider in October 1985 is reflected in the increase in the peak luminosity by about four orders of magnitude, and it is now within an order of magnitude of the design report.

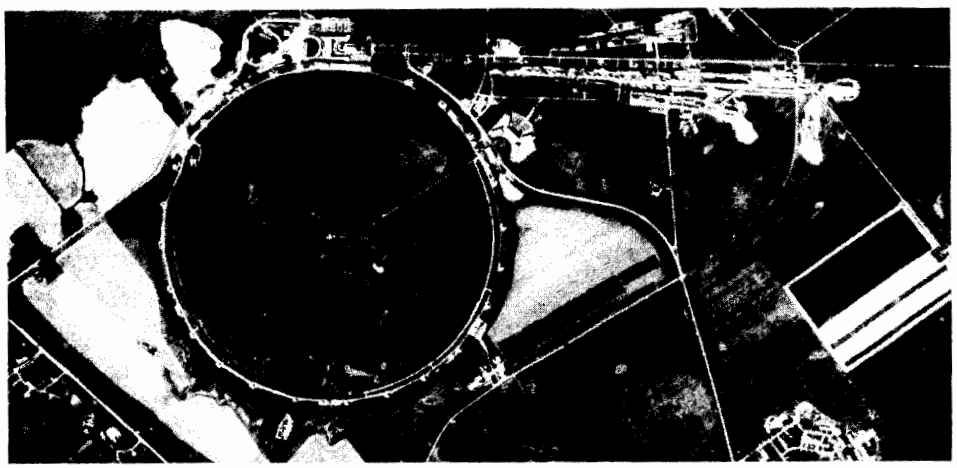

Table II shows these accomplishments sorted into three categories: TEVATRON, Antiproton Source, and antiproton production. This table also demonstrates the progress that has been made in all areas since the initial shakedown of the Collider in November 1986 after the civil construction period.

Table III (page 6) sorts these accomplishments according to antiproton transmission, proton transmission, and factors which can degrade the luminosity. At this time, the worst offender in expected antiproton transmission (64% instead of 100%) occurs in the TEVATRON. More will be said about this later.

*Excerpted from Fermilab TM-1454, "1987 DOE Review - First Collider Run Operation," S. Childress et al. (May 1987).

	Design	Oct 85	Apr 87	Goals Winter 86-87
p/bunch	6E10	2E10	5E10	4E10
$\bar{p}$/bunch	6E10	Few E6	0.91	1E10
number bunches	3x3	1x1	3x3	3x3
$\bar{p}$ extracted/bunch		Few E8	2.6E10	2.7E10
MR transmission		0.25	0.85	3/4
coalescing efficiency (proton)		0.2-0.4	0.70	1/2
transverse emittance 95%	24	15-50	20-25 (p)	24
Normalized (πx10^{-6}m)			30-40 ($\bar{p}$)	
bunch length luminosity reduction		0.8	0.85	0.9
luminosity	10^{30}	Few 10^{24}	10^{29}	10^{29}
average minimum storage time required from $\bar{p}$ production rate	2 hr		7 hr	5-6 hr
$\bar{p}$ accumulation rate	11xE10/hr	10^9/hr	1.2x10^{10}/hr	1.5xE10/hr

TABLE I. TEV I Collider history and goals.

TEVATRON	Design (TeV I)	Oct 85	Nov 86	Apr 87	Goal 87
energy	0.8-1.0 TeV	0.8 TeV	0.9 TeV	0.9 TeV	0.9 TeV
number of bunches	3x3	1x1	1x1	3x3	3x3
luminosity	10^{30}cm^{-2}sec^{-1}	Few 10^{24}	~10^{26}	10^{29}	10^{29}
factor from design		Few x 10^5	~10^4	10	~10
$\bar{p}$ source (8 GeV)					
$\bar{p}$/10^{12} protons	3x10^7	10^6	0.38x10^7	0.68x10^7	0.8x10^7
$\bar{p}$/hr	10^{11}	10^9	0.3x10^{10}	1.2x10^{10}	1.5x10^{10}
$\bar{p}$ total stack	5x10^{11}	10^{10}	0.9x10^{11}	3.8x10^{11}	10^{11}
factor from design ($\bar{p}$/hr)		150	33	8.3	7
MR (target production)					
proton intensity	2x10^{12}	1x10^{12}	0.8x10^{12}	1.3x10^{12}	1.5x10^{12}
target cycles/hr	1800	720	990	1400	1200
factor from design		5	3.3	2.0	2

TABLE II. TEVATRON Collider $\bar{p}$-p.

	Design	Apr 87	Missing Factor	Goals Winter 86-87	Goal Factor 87
$\bar{p}$ extracted from accumulator/bunch		2.6E10		2.7E10	
$\bar{p}$ MR transmission		0.77		3/4	
$\bar{p}$ coalescing efficiency		0.70		1/2	
$\bar{p}$ transmission from MR to TeV low-β		0.64		1	
$\bar{p}$ overall transmission		0.35		.37	
$\bar{p}$ stored/bunch	6E10	0.91	6.6	1E10	6
p extracted from booster		1.5E11			
p MR transmission		0.75		3/4	
p coalescing efficiency		0.62		1/2	
p transmission from MR to TeV low-β		0.8		1	
p overall transmission		0.37		.37	
p stored/bunch	6E10	5.6E10	1.07	4E10	1.5
number of bunches	3x3	3x3		3x3	1
transverse emittance 95% normalized	24	20-25 (p)		24	1
(πx10^{-6}m)		30-40 ($\bar{p}$)			
bunch length luminosity reduction		0.85	1.2	0.9	1.1
luminosity	E30	10^{29}	10	E29	10
$\bar{p}$ accumulation rate	11xE10/hr	1.2E10	9.2	1.5xE10/hr	7
average minimum storage time required from pbar production rate	2 hr	6.5 hr		5-6 hr	

TABLE III. TeV Collider missing factors and goals.

Antiproton Transfer

Each step of the antiproton transfer process has the potential for completely obliterating the antiprotons before a store begins. Most steps have failed at least once and Fig. 1 summarizes the failures of antiproton transfers since February 2. The months of December and January were spent getting the mere mechanics of the transfer under control, and that was no small task. It is worth noting that once a failure was identified and corrected, it tended to stay corrected. Week nine stands out with a rash of failures since it followed (the last) three-day maintenance period.

The transmission of the antiprotons is summarized in a little more detail as follows: Accumulator to Main Ring injection, 87%; Main Ring injection to 150

GeV, 88%; coalescing, 70%; transfer from Main Ring to TEVATRON, 72%; TEVATRON acceleration, 99%; low-beta squeeze, 90%; overall efficiency from Accumulator to low beta, 34%. This represents the average of stores 910 to 920. Coalescing includes bunch monitor calibration of 0.80. The overall transmission from the Accumulator to a single bunch at low beta averaged about 34% by the end of April. (It started out in the few per cent range at the beginning of the run.) The biggest losses are associated with coalescing and the transfer into the TEVATRON; together they account for a loss of about a factor of two. Most of the loss in the TEVATRON occurs within the first second.

WEEK #	6	7	8	9	10	11	12	13	14	15	16	17	18	19	TOTAL
I65 CARD SCRAMBLED INJECTION			1												1
CONSOLE DIED			1												1
DIDN'T COALESCE				1											1
DIED AT .7 SEC IN MR				1											1
PBAR DAMPERS				2	1										3
E48 KICKER				1			1								2
CO ABORT KICKER				1										1	2
SEQUENCER				1							1				2
VACUUM VALVE STARTING TO CLOSE				1											1
UNKNOWN LOSS IN MR				1				1							2
PBAR ARF2-3 PROBLEMS						1									1
E17 PBAR KICKER							1								1
TUNES ADJUSTED WRONG							1								1
KICKER TRIGGER PROBLEMS								1							1
53 MHZ BUNCHING TRIGGER WRONG											1		1		2
TEV FAST BYPASS												1			1
FORGOT TO DISABLE BLM ABORTS												1			1
TRANSFERS THAT FAILED			2	9	1	1	3	2			2	2	1	1	24

FIG. 1. Reasons for antiproton transfer failures.

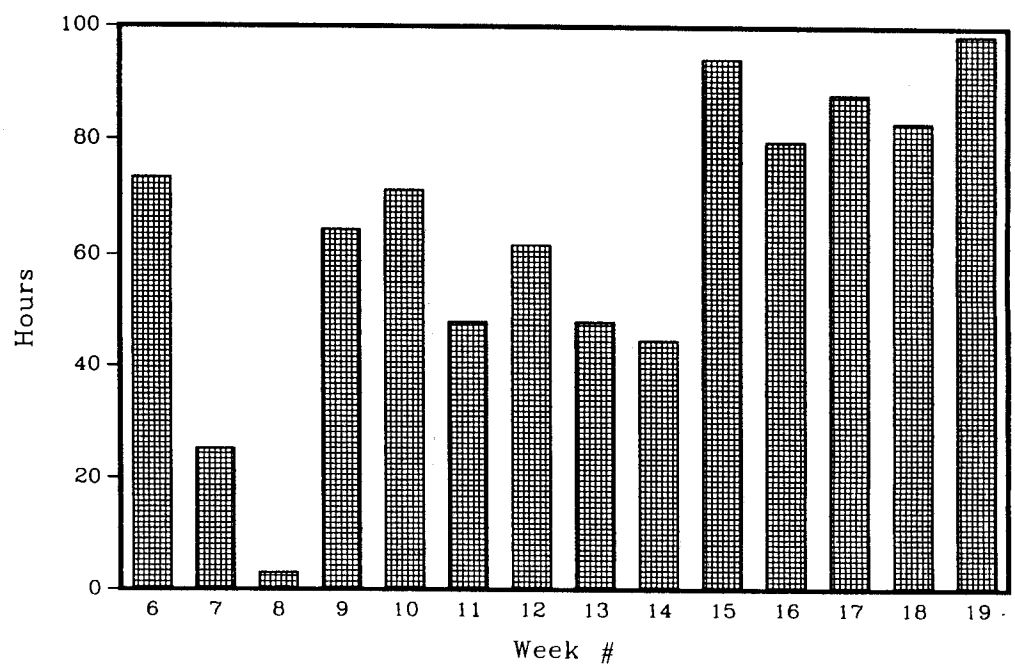

FIG. 2. Integrated store hours/week since February 2.

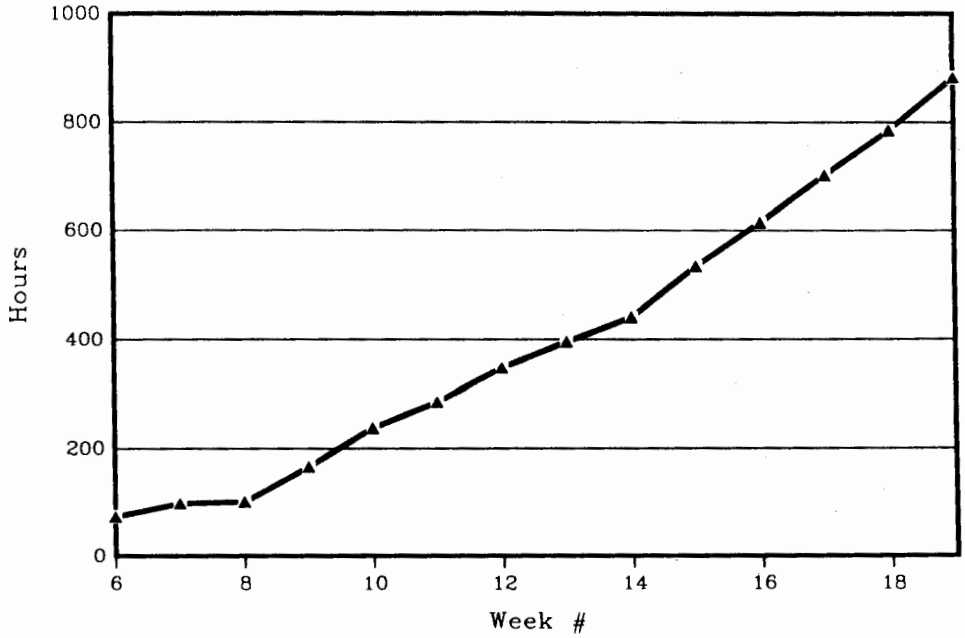

FIG. 3. Integrated store hours since February 2.

Once the transfer process is completed and a store has begun, the burden shifts to the TEVATRON which must maintain the store. Figures 2 and 3 summarize the time that the TEVATRON was acutally storing colliding beams. The peak week had 94.3 hours which represents 56% of clock time.

Figure 4 shows the reasons stores ended. About half the stores were deliberately ended, and less than 10% of the stores were ended due to the fact that the TEVATRON uses superconducting magnets.

WEEK #	6	7	8	9	10	11	12	13	14	15	16	17	18	19	TOTAL
SHOT MASTER ENDS	3	1		7	5	1	1	1	3	6	5	4	4	4	45
CORRECTION ELEMENTS	1	1			1	1	1	2							7
BO QUADS	1												1		2
BLM/BPM	1														1
POWER SUPPLIES	2			1						1		1		3	8
QPM	1														1
VACUUM		1					1	1							3
RF		1					1					1			3
STUDIES					2							1			3
CRYO						1	2	1							4
KICKERS						2		1		1					4
POWER GLITCH						1									1
MR BEAM INDUCED QUENCH										1	1		1		3
FEEDER FAULT									1						1
TYPE O ABORT								1							1
PREDET ARC DOWN												1			1
MR WATER PUMP TRIPPED													1		1
CONTROLS														2	2
AIR CONDITIONER TRIPPED														1	1
STORES TOTAL	9	4	0	8	8	6	6	7	4	9	6	8	7	10	92

FIG. 4. Reasons for end of stores.

Reliability

There were neither regularly scheduled Accelerator maintenance periods nor accesses to the detectors during this Collider run. This apparently revolutionary approach did not take long to reap benefits because the reliability of the accelerator complex was the best it has ever been in recent memory.

This can be seen from Figures 5 and 6 which summarize reliability from two viewpoints - stacking and storing - during 13 weeks of the run. The figures indicate that, of the total calendar time, there were collisions taking place 35% of the time and antiproton production was taking place 48% of the time. TEVATRON downtime by itself prevented collisions 9% of the time, and antiproton production was prevented 22% of the time due to failures in the Linac, Booster, Main Ring, Debuncher, or Accumulator.

STACKING RELIABILITY SINCE FEBRUARY 2

WEEK #	STACK TIME	STACKING FAILURE	SETUP/ QUIET TIME	M&D	TOTAL
6	78.32	41.92	47.6		168
7	45.54	21.95	34.51	66.0	168
8	23.10	23.42	32.48	89	168
9	95.12	26.42	45.46		168
10	105.2	17.62	45.18		168
11	104.88	39.8	23.32		168
12	86.48	62.01	19.51		168
13	116.46	16.16	35.38		168
14	63.33	60.98	42.69		167
15	96.14	28.11	43.75		168
16	83.74	68.46	15.8		168
17	74.06	44.39	49.55		168
18	106.56	22.38	39.06		168
19	106.56	18.89	42.55		168

FIG. 5. Stacking reliability since February 2.

STORING RELIABILITY SINCE FEBRUARY 2

WEEK #	STORE TIME	TEV DOWNTIME	STACK W/O STORE	SETUP/ STUDY	M&D	TOTAL
6	73.42	28.13	43.31	23.14		168
7	25.25	12.97	28.52	35.26	66	168
8	3	14.18	23.1	38.72	89	168
9	64.48	12.0	54.38	37.14		168
10	71.30	6.43	41.94	48.33		168
11	47.85	29.07	68.39	22.69		168
12	61.8	17.25	38.34	50.61		168
13	47.9	12.1	82.16	25.84		168
14	44.59	17.82	32.66	71.93		167
15	94.3	8.75	16.79	48.16		168
16	79.81	7.47	46.9	33.82		168
17	88.05	20.92	16.5	42.53		168
18	83.15	31.9	36.48	16.47		168
19	98.6	14.53	32.4	22.47		168

FIG. 6. Storing reliability since February 2.

Figure 7 (page 10) shows the individual downtime for each of the accelerator systems. Since these are individual system downtimes, they do not necessarily add up to the total downtime. For example, controls downtime includes maintenance on computer consoles which does not necessarily prevent stacking or storing.

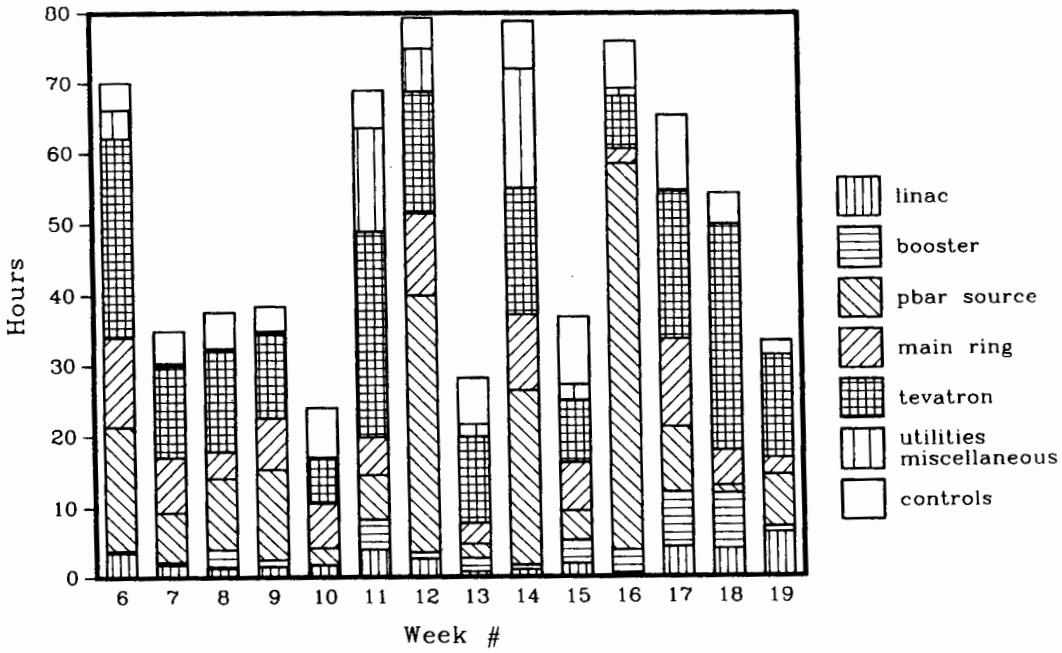

FIG. 7. Systems downtime by week since February 2.

Luminosity

The luminosity given in this report is based on original estimates of the response of the Accelerator detectors used to measure the beam intensities. These estimates are being re-evaluated and now it appears that the luminosity was actually higher than reported here by a factor of about 1.5.

Figure 8 shows the progression of the peak luminosity throughout the run. It grew exponentially for the first seven weeks as a whole host of carefully controlled adjustments were made in *all* parts of the accelerator complex. It then reached a plateau below 1×10^{29} for about a month, and then went back up.

Figures 9 and 10 show the "bottom line" for a collider: the integrated luminosity. The integrated luminosity per week increased significantly every week since the beginning of February with one exception. Week 17 had sequential failures in the Linac, Booster, Debuncher, and Accumulator which limited the antiproton production rate, and eventually an access to the Debuncher required dumping the stack and starting over. In spite of all this, by the beginning of May the integrated luminosity surpassed 10 nb^{-1} per week and approached 35 nb^{-1} for the run.

The Collider Detector Facility (CDF) luminosity lifetime averaged about 10 hours, which is about half of the TeV I design value. Early in a store, the lifetime is about 7-8 hours, and increases as the store progresses to about 15-20 hours for stores over 15 hours. The lifetime is dominated by a growth of the transverse beam size at a rate of a few microns per hour at the collision point. The primary source of this growth has not yet been identified, but if it can be found and corrected it could be worth a factor of two in the integrated luminosity.

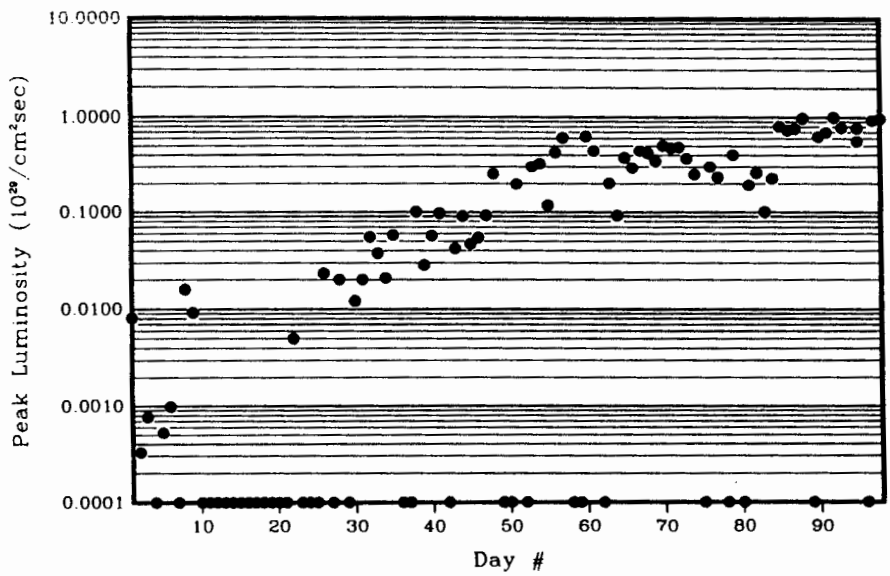

FIG. 8. Peak luminosity/day since February 2.

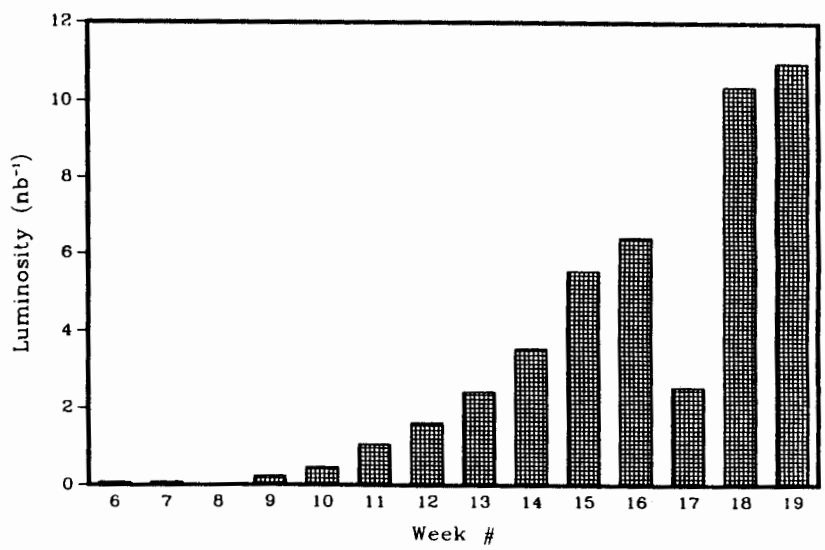

FIG. 9. Integrated luminosity/week since February 2.

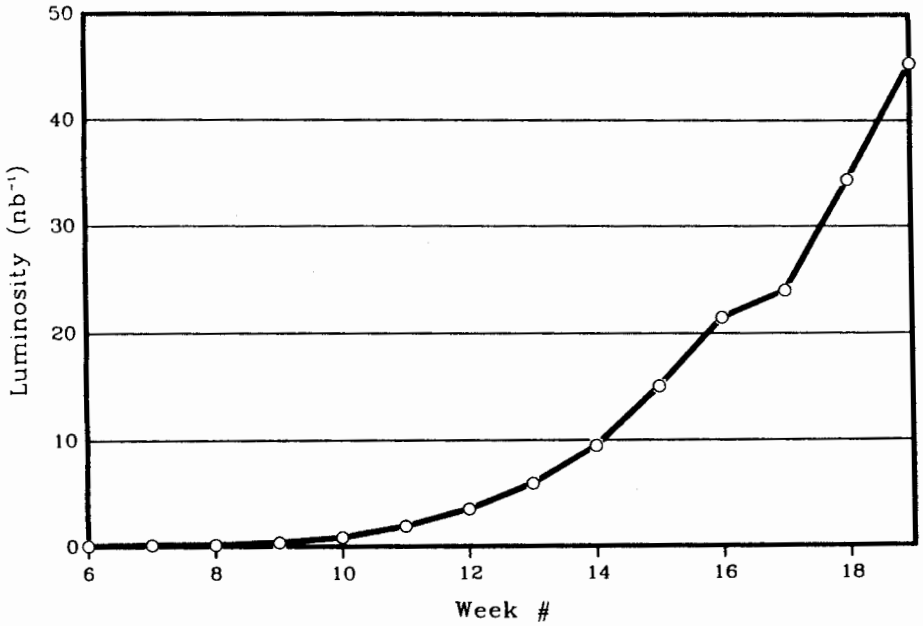

FIG. 10. Integrated luminosity since February 2.

In April a new low beta was implemented which increased the peak luminosity at CDF by a factor of 1.4. This yielded a net gain in the integrated luminosity even though the luminosity lifetime was a little worse. This so-called mini-beta was accomplished by changing the currents in the B0 low-beta quads.

Unusual Quenches

The only real problem associated with 900 GeV is the sensitivity of the superconducting magnets to otherwise insignificant beam loss. They can withstand much less loss than at 800 GeV because they have been pushed much closer to their quench currents. When antiprotons are in the TEVATRON, all the beam-loss-monitor aborts are deliberately disabled. This would not be a problem at all if everything always performed perfectly.

The first quench of a TEVATRON magnet with antiprotons occurred on January 17, 1987, when there were about 9×10^8 antiprotons in a single bunch. The quench was caused by a malfunction of the antiproton abort kicker at C17 which did not properly deflect the antiprotons into their abort dump at C0. When this happens, the antiprotons continue going until they pass through the proton abort kicker at B48 which in turn deflects them into the dipoles at B4.

The Main Ring accelerates over 1.3×10^{11} protons 1400 times per hour for antiproton production at the same time (and in the same tunnel, of course) that the

Collider is running at 900 GeV. Extraction of the proton beam from the Main Ring at F17 can malfunction in a perverse manner and cause sufficient beam spray in the tunnel to induce a quench in the TEVATRON at F17. Three stores ended in this manner.

Another potential quench situation occurs when the TEVATRON rf misbehaves during a store and the beam debunches. This uncaptured beam would normally spiral inward as it slowly loses energy due to synchrotron radiation and eventually leave the TEVATRON after 2-3 hours. If the abort kickers fire for some reason, and there is enough debunched beam in the TEVATRON, then it can cause a quench in one or more locations. The worst of these happened on the last day of April and caused quenches in four places around the ring.

Improvements for the Next Collider Run

It should not surprise anyone that the Main Ring aperture has shrunk after it ceased being the last accelerator in the chain. This is primarily due to several aperture-restricting magnets which have been added for TEVATRON injection, and antiproton production and injection. In addition, the vertical overpasses around B0 and D0 not only restrict the horizontal aperture locally, but also introduce vertical dispersion which compromises the vertical aperture in the rest of the ring. Progress is continually being made by identifying the offending restrictions and either moving them or installing larger aperture devices. This will necessarily continue during the fixed-target run because fixed-target experiments always need more beam than is available.

The TEVATRON has come up with one big surprise that has been avoided operationally at a cost in setup time. The design report supposed that the TEVATRON could come out of a flattop store and then be reliably set at 150 GeV for the few minutes required for injection of protons and antiprotons. This has not been feasible due to a continually drifting chromaticity. The amount of the drift is as much as 20 units in the first few minutes after it has come out of a flattop store and been put at 150 GeV. The drift becomes slower, and after about an hour it can be adequately corrected manually. A more automatic method of chromaticity correction will cut down on the setup time and provide more time for stores.

Another improvement that will be attempted for the next run is to control the transverse emittances of the antiprotons. When they enter the Main Ring, the emittances are about 8π mm-mrad. This increases to about 25π mm-mrad by the time they are first observed in the TEVATRON. This increase may be due to injection steering mis-matches into the Main Ring and then into the TEVATRON, but they may also be due to emittance blowup during coalescing. This

will be investigated before the next run using an updated flying-wire system in the Main Ring. The emittance blows up to about 35π mm-mrad during TEVATRON acceleration and the low-beta squeeze. This last increase is very likely due to the antiprotons being driven onto tune resonances because of the beam-beam interaction. During the present run, new tune-measuring devices were installed and have just begun to be used to their full potential. By the next run, they should be able to sort out just what is happening with the antiproton emittances. If the emittances can be controlled completely, it is worth a factor of three in the peak luminosity.

The success of this first run is due to those people who worked to prevent repeated equipment failures and kept up the struggle to improve each step of the transfer process. Their efforts have paid off.