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1987 DOE Review - First Collider Run Operation

S. Childress, J. Crawford, G. Dugan, H. Edwards, D.A. Finley, W.B. Fowler, M. Harrison,
S. Holmes, J.N. Makara, E. Malamud, T.J. Peterson, and D. Young
Fermi National Accelerator Laboratory
Batavia, IL 60510 USA

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DOE REVIEW

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John Crawford
David A. Finley

COLLIDER

I. OPERATION OF THE FIRST 1.8 TEV COLLIDER RUN

Overview

This first 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 1 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 4 orders of magnitude, and it is now within an order of magnitude of the original design report.

Table 2 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 3 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.

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. And their efforts have paid off.

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 Table 4 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 9 stands out with a rash of failures since it followed (the last) 3 day maintenance period.

The transmission of the antiprotons is summarized in a little more detail in Table 5. 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 percent range at the beginning of the run.) The biggest losses are associated with coalescing and the transfer into the Tevatron which together account for a loss of about a factor of two. Most of the loss in the Tevatron occurs within the first second.

Once a the transfer process is completed and a store has begun, the burden shifts to the Tevatron which must maintain the store. Figures 7 and 8 summarize the time that the Tevatron was actually storing colliding beams. The peak week had 94.3 hours which represents 56% of clock time. Table 6 shows the reasons that 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.

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 since the reliability of the accelerator complex was the best it has ever been in recent memory.

This can be seen from Figures 9 which summarizes reliablility from two viewpoints - stacking and storing - during 13 weeks of the run. As can be seen from Figures 9a and b, 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.

Figure 9c 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.

Luminosity

Figure 10 shows the progession 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 1E29 for about a month, and then went back up.

Figures 11 and 12 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 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 2 in the integrated luminosity.

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 new low beta was accomplished by changing the currents in the B0 low beta quads. Before the second collider run this solution should be re-evaluated in order to alleviate some of the problems which show up at C0 and E0.

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 since 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 9E8 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 1.3E11 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 looses 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.

2. 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 since fixed target experiments always need more beam than is available.

The Tevatron has come up with one big suprise 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 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 3 in the peak luminosity.

3. TEVATRON UPGRADE

The present design for a second low beta collision region at D0 requires injecting into the Tevatron with a horizontal dispersion mismatch at the E0 injection point. This mismatch would be comparable to the vertical mismatch with which injection is presently done. The effects of such an additional mismatch on the transverse emittances will be investigated by injecting protons when the low beta quads at B0 are partially energized so that the lattice has a mis-matched horizontal dispersion at the injection point. If it turns out to be important to the luminosity, then techniques to eliminate these mis-matches will be implemented.

The long range upgrade of the Tevatron calls for dozens of colliding bunches. This will not work unless the bunches collide at a minimum number of locations around the ring. If they were allowed to collide all around the ring, the beam-beam interaction would be sufficient to cause the particles to occupy resonances which would drive them out at an unacceptable rate. In order to accomodate dozens of bunches, electrostatic beam separators must be developed which cause the bunches to pass one another side-by-side except near the interaction points where they still collide head-on. The present design calls for separation in both planes giving spiral orbits through most of the ring. Some of the effects on beam lifetime will be investigated with protons by using the dipole correction elements to create spiral orbits.

In the upcoming months, the feasibility of a Tevatron lattice design which incorporates a third low beta region at A0 will be investigated. One feature would include removing the magnets from the A0 straight section which are used for fixed target extraction, and putting them back for fixed target runs. A similar arrangement has been partially implemented at D0, where additional extraction elements reside. Incorporation of a third low beta in the lattice may require an upgrade of the higher order correction element supplies.

TABLE 1

TEV I COLLIDER HISTORY AND GOALS

	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	3×3	1×1	3×3	3×3
$\bar{P}$ 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% NORMALIZED ($\pi \times 10^{-6}$M)	24	15-50	20-25 (P) 30-40 ($\bar{P}$)	24
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	11×E10/HR	10^{9}/HR	1.2 ×10^{10}/HR	1.5×E10/HR

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TABLE 2
TEVATRON COLLIDER $\bar{P}$-P

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	3×3	1×1	1×1	3×3	3×3
LUMINOSITY	10^{30} $\mathrm{CM}^{-2}\mathrm{SEC}^{-1}$	FEW 10^{24}	$\sim 10^{26}$	10^{29}	10^{29}
FACTOR FROM DESIGN		FEW × 10^{5}	$\sim 10^{4}$	10	~10
$\bar{P}$ SOURCE (8 GEV)					
$\bar{P}/10^{12}$ PROTONS	3×10^{7}	10^{6}	0.38×10^{7}	0.68×10^{7}	0.8×10^{7}
$\bar{P}$/HR	10^{11}	10^{9}	0.3×10^{10}	1.2×10^{10}	1.5×10^{10}
$\bar{P}$ TOTAL STACK	5×10^{11}	10^{10}	0.9×10^{11}	3.8×10^{11}	10^{11}
FACTOR FROM DESIGN ($\bar{P}$/HR)		150	33	8.3	7
MR (TARGET PRODUCTION)					
PROTON INTENSITY	2×10^{12}	1×10^{12}	0.8×10^{12}	1.3×10^{12}	1.5×10^{12}
TARGET CYCLES/HR	1800	720	990	1400	1200
FACTOR FROM DESIGN		5	3.3	2.0	2

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TABLE 3 TEV COLLIDER MISSING FACTORS AND GOALS

	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	3×3	3×3		3×3	1
TRANSVERSE EMITTANCE 95% NORMALIZED ($\pi\times10^{-6}$M)	24	20-25 (P) 30-40 ($\bar{P}$)		24	1
BUNCH LENGTH LUMINOSITY REDUCTION		0.85	1.2	0.9	1.1
LUMINOSITY	E30	10^{29}	10	E29	10
$\bar{P}$ ACCUMULATION RATE	11×E10/HR	1.2E10	9.2	1.5×E10/HR	7
AVERAGE MINIMUM STORAGE TIME REQUIRED FROM PBAR PRODUCTION RATE	2 HR	6.5HR		5-6 HR	

REASONS TRANSFERS FAILED TABLE 4

WEEK #	6	7	8	9	10	11	12	13	14	15	16	17	18	19	TOTAL
165 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

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REASONS STORES ENDED TABLE 6

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 0 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

Table 5

Antiproton transmission efficiencies

87%	Accumulator to Main Ring injection
88%	Main Ring injection to 150 GeV
70%	Coalescing
72%	Transfer from Main Ring to Tevatron
99%	Tevatron acceleration
90%	Low beta squeeze

34% Overall efficiency from Accumulator to Low beta

This represents the average of stores 910 to 920.
Coalescing includes bunch monitor calibration of 0.80

INTEGRATED STORE HOURS/WEEK SINCE FEBRUARY 2

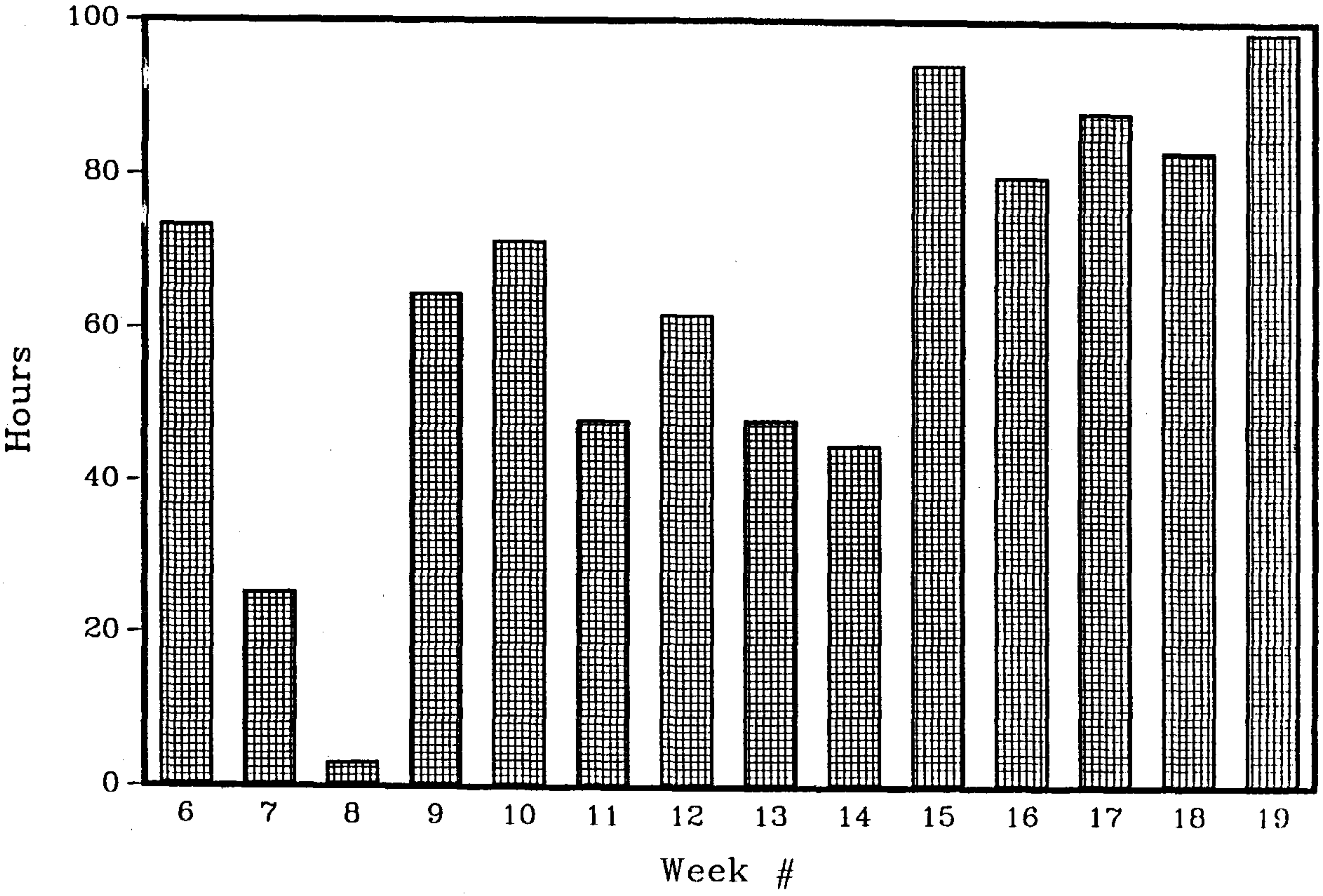


FIGURE 7

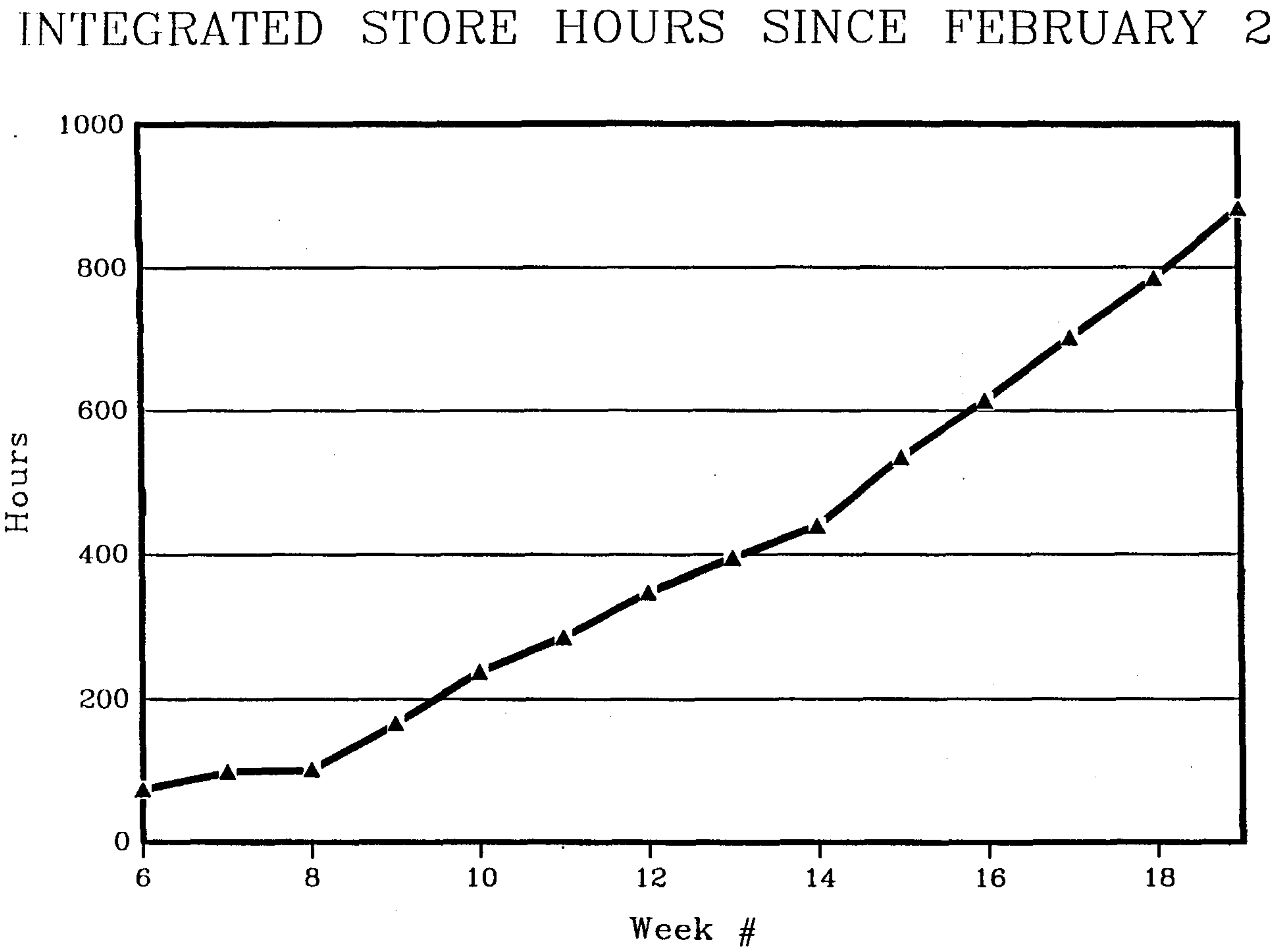

INTEGRATED STORE HOURS SINCE FEBRUARY 2
1000
800
600
400
200
0
Hours
6
8
10
12
14
16
18
Week #

FIGURE 3

FIGURE 9a

May 4, 1987

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	89.0	168
9	95.12	26.42	46.46		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

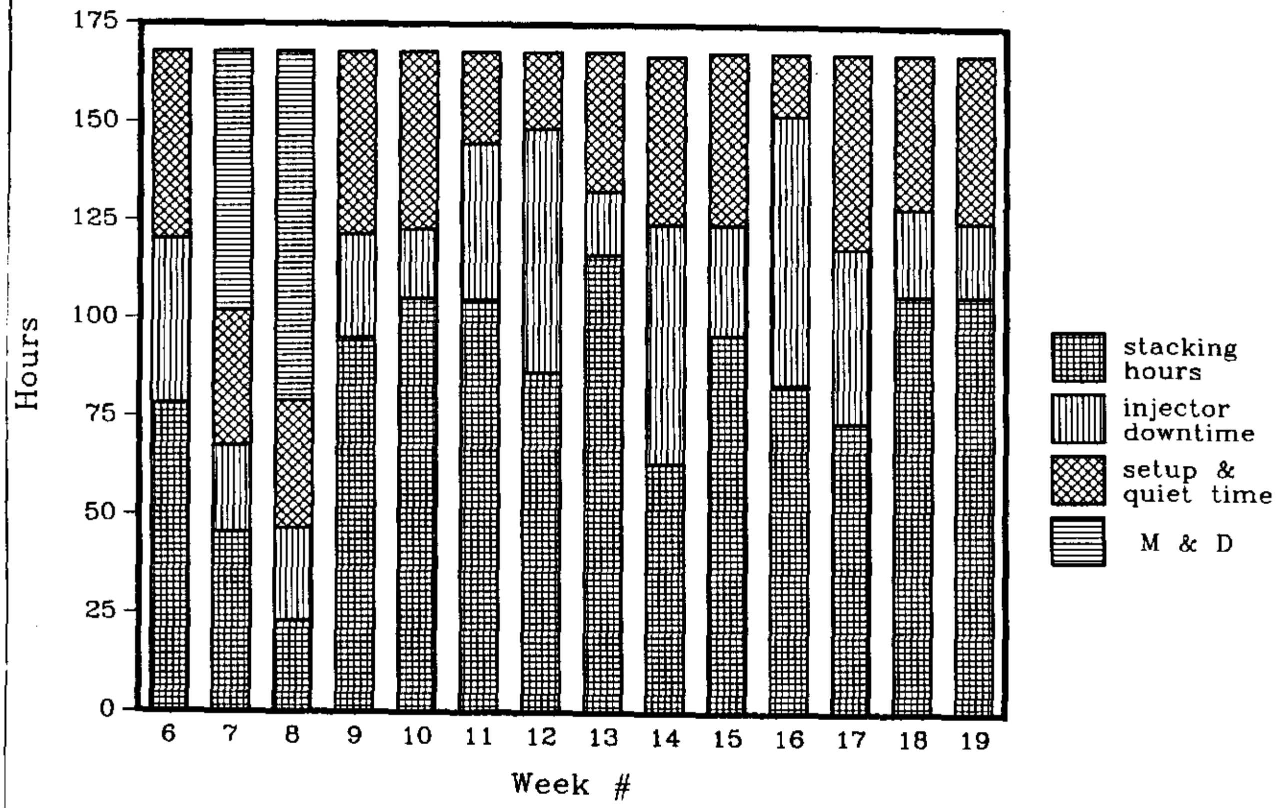
May 4, 1987

STORE RELIABILITY SINCE FEBRUARY 2

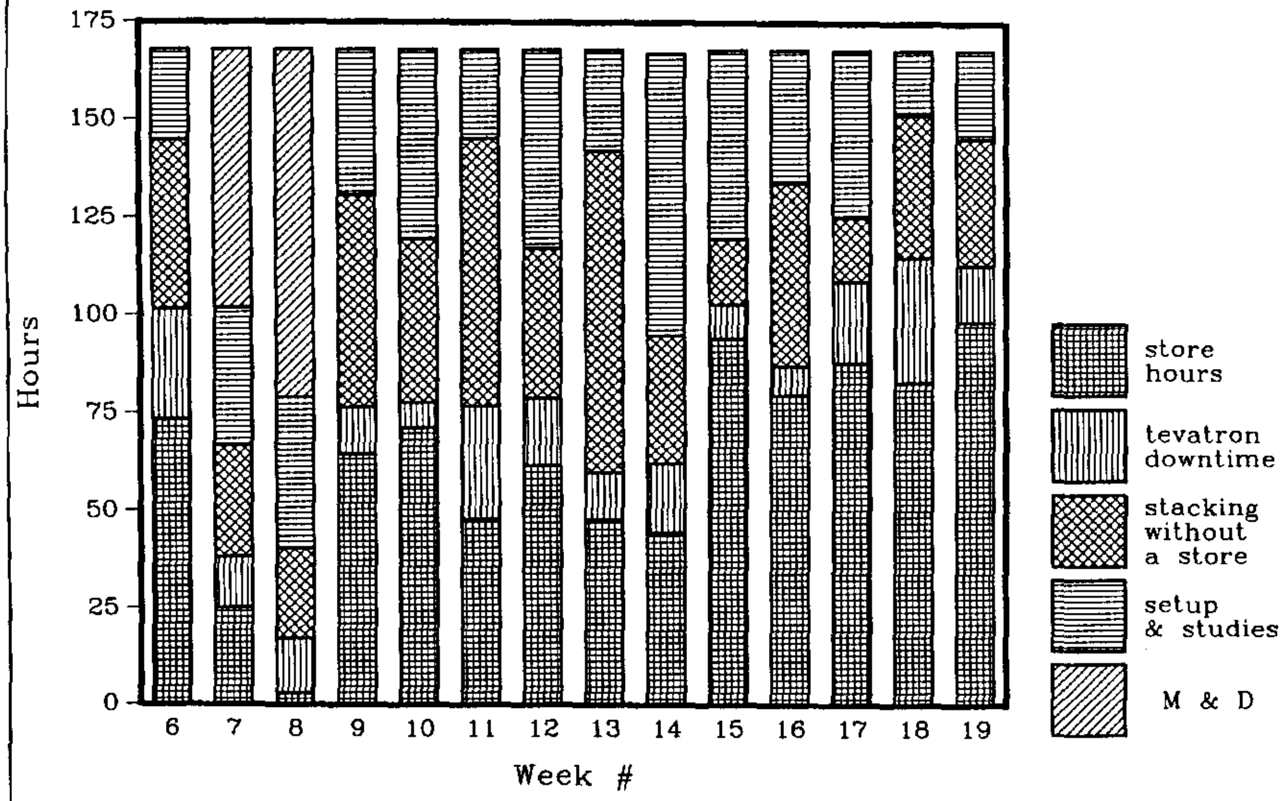
WEEK #	STORE TIME	TEV DOWNTIME	STACK W/O STORE	SETUP/ STUDY	M&D	TOTAL
6	73.42	28.13	43.31	23.14		168
7	25.25	12.97	28.52	35.26	66	168
8	3	14.18	23.1	38.72	89	168
9	64.48	12.0	54.38	37.14		168
10	71.30	6.43	41.94	48.33		168
11	47.85	29.07	68.39	22.69		168
12	61.8	17.25	38.34	50.61		168
13	47.9	12.1	82.16	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	31.90	36.48	16.47		168

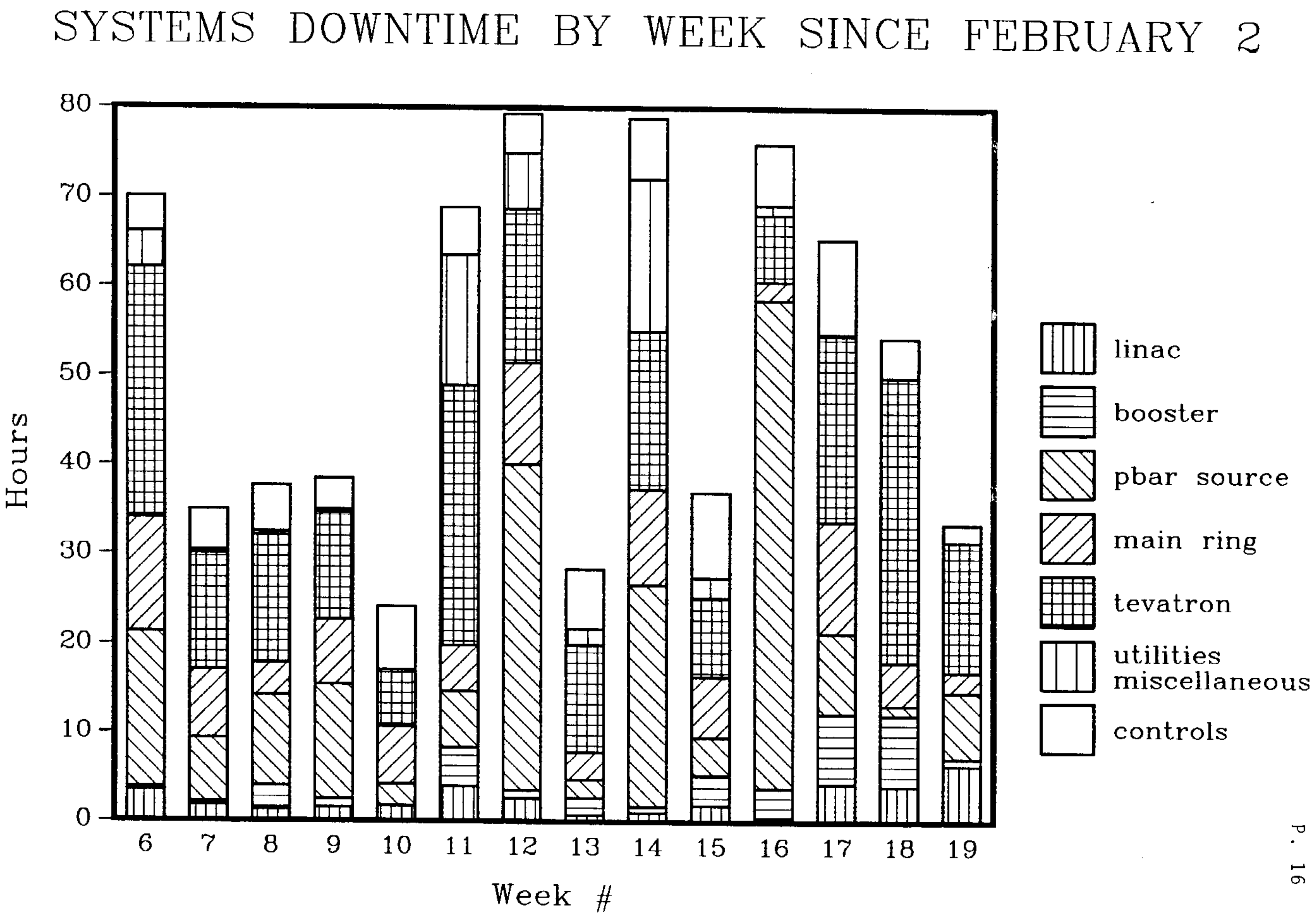
FIGURE 9b

STACKING RELIABILITY SINCE FEBRUARY 2



STORING RELIABILITY SINCE FEBRUARY 2





SYSTEMS DOWNTIME BY WEEK SINCE FEBRUARY 2

FIGURE 9c

PEAK LUMINOSITY/DAY SINCE FEBRUARY 2

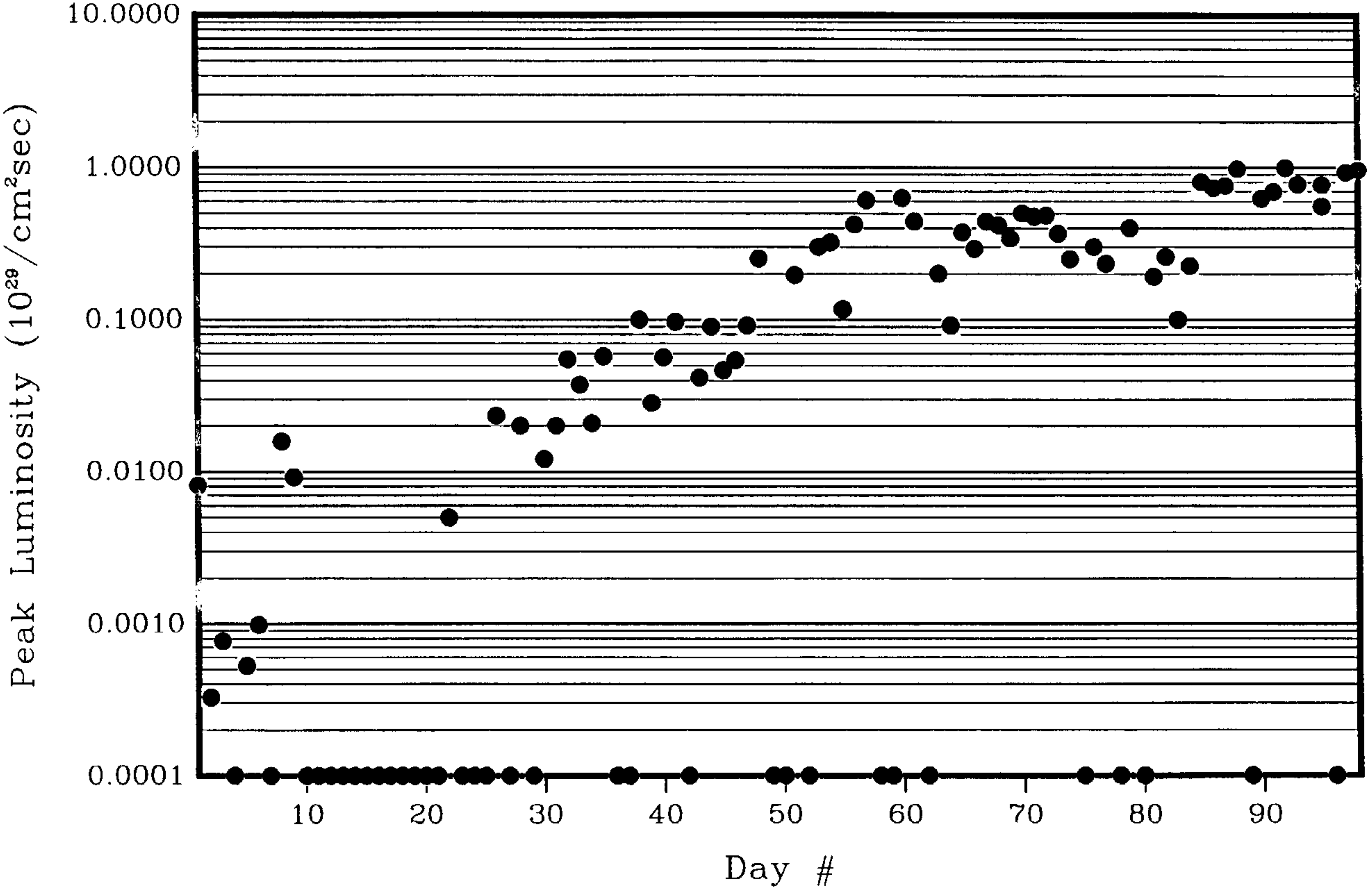
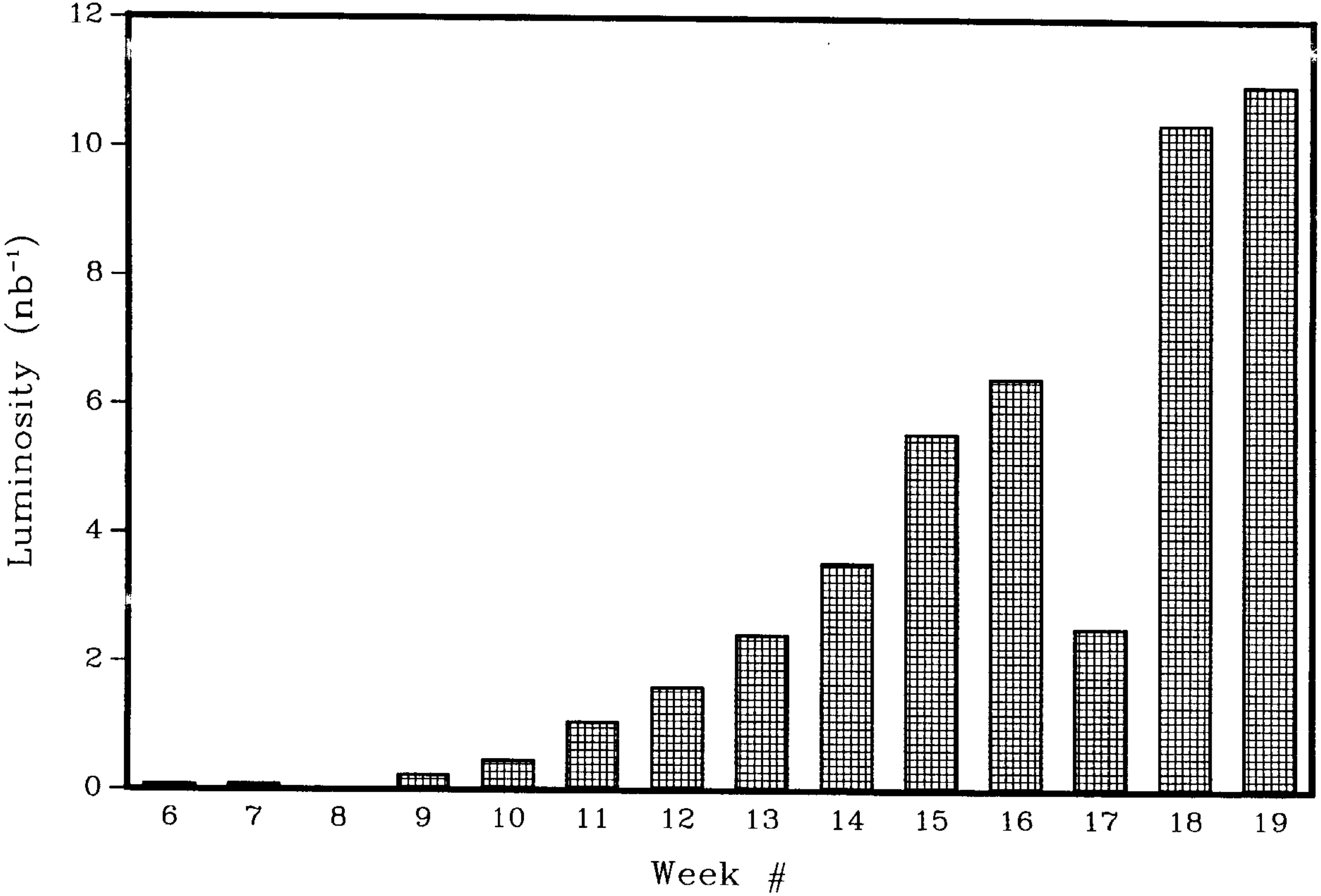
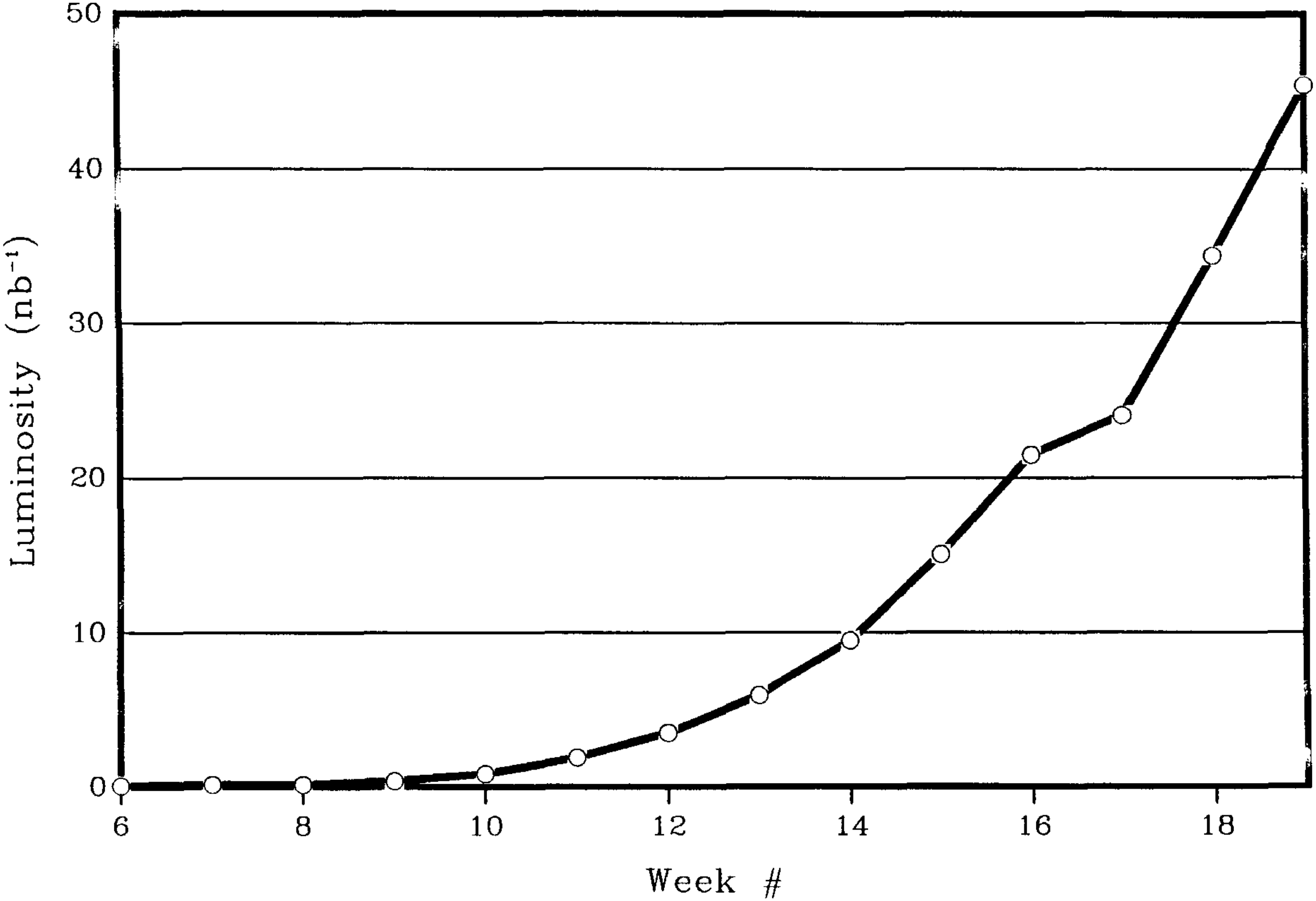


FIGURE 10



INTEGRATED LUMINOSITY/WEEK SINCE FEBRUARY 2

FIGURE 11



INTEGRATED LUMINOSITY SINCE FEBRUARY 2

FIGURE 12

PBAR SOURCE STATUS - G. Dugan

(a). Operation and Reliability

A concise summary of pbar source operation since February 2 is presented in Table 1. This shows, on a weekly basis, the number of pbars produced, the time available for stacking (pbar production), the average stacking rate, and the peak stack achieved that week. One milliamp is equal to 10**10 pbars.

Table 2 illustrates the pbar source reliability, by showing the times when pbar stacks were dumped, and the amounts lost. As can be seen, reliability has been relatively high (except for week 12). The lower part of table 2 shows the duration of continuous stacks in the Accumulator. The average length of a sustained stack since February 2 has been 9 days.

The best stacking rate acheived was about 1.2 ma/hr. The section below, labelled "Performance", presents an analysis of the factors contributing to this rate. The average stacking rate shown in table 1 is of course lower than this, for a variety of reasons. One of the most important reasons is that the stacking rate is a function of the stack intensity, as discussed below in the "Performance" section. Thus, for example, during week 12, when the stack was lost frequently, much of the time was spent stacking with a low intensity in the core, so the average rate was high. More typical operation involves stacking with 20 to 30 or more milliamps in the stack, for which the stacking rate is significantly lower than for an almost empty machine.

(b). Performance

A discussion of the performance of the pbar source can be broken down into two broad topics: the rate at which pbars are stacked into the Accumulator core, and the quality of the pbar beam which is delivered to the Main Ring and Tevatron. The first topic also involves the performance of the Main Ring as a supplier of 120 GeV protons for pbar production.

The first topic is summarized in table 3, which breaks down the pbar production and collection process into a number of stages, and for each stage shows the design performance, the performance acheived by 4/13/87, and the "missing factor" for each stage, which is defined as the design performance divided by the actual performance. Also shown for comparison is the performance in November, 1986.

A perusal of the "missing factors" gives a good summary of the source/Main Ring performance as a producer and collector of antiprotons. Stage 1, the Main Ring intensity on target, is low by a factor of 1.5 from design, but has been steadily improving (in fact, since 4/13/87, it has improved to close to 1.5x10**12). The largest single missing factor is at stage 2. The bulk of this missing factor has been tentatively attributed to a reduced pbar production cross section (by a factor of 2.5) from what was estimated in the original design report. In addition, the beam line transmission is no better than about 85% theoretically; these two effects account for a missing factor of 2.95. Further studies of the cross section are planned for this summer, using a Cerenkov counter to identify the pbars. The need to make up this missing factor in pbar flux at this early stage of the production/collection process plays a major role in determining the shape of the source improvement programs in the next two years.

The missing factor at stage 3 is due to the inability to bunch rotate a 3% momentum spread into .2% in the Debuncher with full efficiency. This is related both to the time spread of the Main Ring proton beam on target, which is somehwat broader than the design, and to the reduced voltage available in the Debuncher RF system (4 MV vs. the design of 5 MV). Part of the improvement program discussed below will address the problem of more voltage for the Debuncher RF.

The origin of the missing factor at stage 4 is inefficiency in the beam transfer from Debuncher to Accumulator. This inefficiency is not well understood; in studies periods last December, better than 95% transfer efficiency between the rings was acheived for proton beams of longitudinal and transverse emittance comparable to that of the pbar beam. The limited vertical acceptance of the Accumulator (7 pi mm-mrad, rather than the design of > 10 pi mm-mrad) is certainly contributing to this problem; studies of and modifications to the Accumulator are planned this summer to improve the vertical acceptance.

At stage 5, the small missing factor of 1.05 is due to inefficiency in RF stacking from the injection orbit to the edge of the stack tail; it is actually an estimated upper limit, since this efficiency is diffcult to measure.

The stacking efficiency quoted in table 3, which is the ratio of the beam deposited on the edge of the stack tail to that accumulated in the core, is actually better than the design. This number is a function of the stack intensity; the number in table 3 was recorded when the stack contained 18x10**10 pbars. At higher intensities, the stacking efficiency declines: this is due to the finite core lifetime of about 300 hours, undesired transverse heating of the core by the stack tail cooling system, and less than optimum performance of the core transverse cooling systems. The stacking efficiency with 30x10**10 pbars in the stack is more like 70%. Improvements in the control of the stack tail heating, and in the core transverse cooling, are both planned for this summer; these are expected to improve the stacking efficiency at high stack intensities.

The Main Ring cycle rate of 1400/hour was acheived with a repetition period of 2.4 seconds. Further reductions in the repetition period will be very difficult due to a number of fundamental limits in the Main Ring. However, the "multi-batch" technique (discussed below in more detail) offers real promise for improvement in the effective pbar production cycle rate for the next run.

The overall missing factor in stacking rate is about 8, which is not far from the goal of 7 for this run. Of this factor of 8, about 2 is due to Main Ring performance, and 4 to the pbar source. The factor of 4 in the source is made from a factor of 2.5, due to the cross section problem mentioned above; the remaining factor of 1.6 is due to the miscellany of other effects discussed above.

The quality of the pbar beam available in the Accumulator core is illustrated by the measured data shown in figures 1 and 2. The transverse emittances in the core, shown in fig. 1, are smaller than the design emittances of 2 pi mm-mrad. This is actually necessary for good Main Ring injection efficiency, since the Main Ring transverse acceptances are 2 pi by 1 pi mm-mrad (horizontal by vertical). For stack intensities up to 30x10**10 pbars, injection efficiency of > 90% is acheivable with careful attention to Main Ring closure. Because of the small Main Ring acceptance, it will be important in the future for the pbar source to maintain core transverse emittances as small as possible.

The core longitudinal density vs stack intensity is shown in fig. 2; the peak densities are below the design density of 6.7x10**10/Hz. Tradeoffs should be possible between longitudinal and transverse densities in the core; these have not been attempted because of the need for the highest available transverse density as discussed above.

Some longitudinal emittance dilution (on the order of 20%) has been observed during the unstacking sequence, when the pbar beam is prepared for transfer to the Main Ring. This is believed to be due to problems in the Accumulator low level RF systems and is under study. Typical longitundinal emittances delivered to the Main Ring have been about 1 ev-sec in 9 53-MHz bunches. This emittance is smaller than the design of 1.44 ev-sec in 13 bunches, because Main Ring coalescing efficiency is considerably better for 9 than 13 bunches. Improvements to the Accumulator h=2 bunchnarrowing RF, which will allow the pbars to be packaged in even fewer bunches, are under consideration.

PBAR SOURCE IMPROVEMENTS

Many of the minor improvements planned for the immediate future (i.e., this summer and fall: in time for the 1987-88 collider run) have been mentioned above in connection with the various aspects of pbar source performance. In addition, a general improvement strategy has been formulated which aims at a factor of 2 increase in stacking rate during the next collider run (1987-88), and an additional factor of 2.5 during the subsequent run (1988-89). It may also be possible to implement higher frequency cooling systems for that run which will improve the extracted pbar beam quality. In subsequent years, the pbar source improvement program which has been formulated for the collider upgrade program will begin to become active.

(1) Near-term improvements

In the first year of the improvement program (1987-88 collider run), the Main Ring intensity will be raised to 1.8x10**12 protons per batch. Using the multi-batch technique, every 5.4 seconds 3 batches will be accelerated to flat top and extracted with a 1.5 sec period. This will yield 2000 pulses/hour; the improvement factor in pbar stacking rate over that shown in table 3 will be (1.8/1.3)x(2000/1400)=2. Provided that the source can handle the 1.5 sec repetition period (which is 33% higher than the design), the stacking rate should increase to 2.4x10**10/hr.

In order to permit the pbar source to operate at the higher cycle rate, in addition to the improvements discussed in the previous section, a significant improvement must be made to the Debuncher betatron cooling system. It is planned to implement optical notch filters for this system which will reduce the system thermal power by about a factor of 2, allowing the cooling gain to be increased and improved cooling performance to be realized. With this improvement and those discussed in the previous section, it is expected that the source can cope with the increased cycle rate and Main Ring intensity.

For the second year (the 1988-89 collider run), improvements are planned to increase the number of pbars per proton collected by the Debuncher. This is a response to the problem of the reduced pbar production cross section. The effective Debuncher momentum acceptance is presently limited at 3% by the size of the RF bucket available for bunch rotation; this will be increased to 4% by an increase in the voltage on the RF cavities. The Debuncher transverse acceptance is presently limited at 20 pi mm-mrad by the size of the stochastic cooling pickup and kicker gaps; these will be increased to open the acceptance up to 30 pi mm-mrad. To compensate for the reduced sensitivity of the pickups and kickers, and the increase in the initial emittance, the Debuncher cooling system power will be increased by x2 by doubling the number of travelling wave tubes. Additionally, some improvements in the AP-2 line and the lithium lens will be required to fully utilize the 30 pi mm-mrad acceptance of the Debuncher. The overall gain in pbars per proton resulting from the increased momentum and transverse accepatnces is estimated to be a factor of 2.5. If this is realized, the pbar stacking rate will be above 5x10**10/hour.

Some modest increase in the quality of the pbar beam sent back to the Main Ring will result from the improvements discussed above under "pbar source performance"; these will be implemented for the 1987-88 collider run. However, major gains can only be made by major changes in the core cooling systems. An R&D effort is currently underway in the pbar source department to develop 4-8 GHz pickups, kickers and associated microwave components for a 4-8 GHz stochastic cooling system. When this R&D effort has come to fruition, 4-8 GHz systems could be installed in the Accumulator core in place of the exitsing 2-4 GHz longitudinal and transverse systems. This will result in significant improvements in the transverse emittance of the extracted pbar beam. The increase in longitudinal density will mean that a larger fraction of the core can be assembled into the same longitudinal emittance, which will make the stack utilization more efficient. Alternatively, the same fraction of the core could be captured into a smaller emittance, which could be beneficial to Main Ring transmission and coalescing efficiency. The present progress of the R&D effort offers some hope that these 4-8 GHz systems could be implemented in time for the 1988-89 collider run.

Table 4 presents a summary of the present cooling systems and illustrates in tabular form the upgrades discussed above.

(2) Collider upgrade (longer-term) improvements

A long-term improvement program, aimed at an increase in the pbar stacking rate by a factor of 4, has been discussed for the pbar source in connection with the collider luminosity upgrade. This increase of x4 in stacking rate is acheived by:

(i) utilizing the "multi-batch" technique to its limit, to obatin 3600 Main Ring targeting cycles per hour; and

(ii) obtaining a factor of x2 increase in the number of pbars produced per proton, by increasing the transverse pbar density at production, and increasing the effective momentum acceptance of the Debuncher.

The near-term improvement program discussed above incorporates some of those elements of the longer-term program which can be implemented soon, and which offer the most promise for improvements. The other elements of the longer-term upgrade will continue to be studied as R&D activties. These include:

(i) Research and development of target sweeping systems, prefocusing lithium lenses, and faster cycling collection lithium lenses, required to acheive the increase in pbar transverse density at production, and to cope with the increased source cycle rate.

(ii) Conceptual system development work for new major 4-8 GHz cooling systems: Debuncher longitudinal cooling, Debuncher betatron cooling, Accumulator precooling, and Accumulator stack tail. These higher frequency systems, which will utilize the components developed in the 4-8 GHz R&D effort discussed above under "near-term improvements", are required to cope with the increased cycle rate.

(iii) Research and development on pickups, kickers, microwave hardware and signal transmission techniques for 8-16 GHz stochastic cooling systems. This very high frequency system will be needed for the Accumulator core when the high stack intensities envisioned for the collider upgrade program are reached.

(iv) Design of conventional system modifications in support of the new cooling systems: for example, the Debuncher and Accumulator lattices need modifications to accomodate the high-frequency cooling systems; a new h=12 RF system is also needed in the Accumulator to accomodate the collider upgrade filling scheme.

Although the details of the longer-term upgrade will undoubtedly evolve as operating experience is gained in the next few years, it seems clear that higher frequency cooling systems (4-8 GHz and above), and more sophisticated targeting and collection schemes, will play a major role in any upgrade scenario. For this reason, these items are at the focus of our present R&D programs.

TABLE 1

Weekly Average Stacking Rates Since 2 February

Week #	Pbars produced	Stacking time	Stacking Rate	Peak Stack
6	39.58 mA	78.32 hrs	.505 mA/hr	13.33 mA
7	28.8	45.54	.632	13.58
8	11.96	23.10	.518	11.96
9	49.89	95.12	.524	16.74
10	49.73	105.2	.473	21.59
11	48.93	104.88	.467	26.07
12	80.06	86.48	.926	33.04
13	81.55	116.46	.700	35.11
14	35.42	63.33	.559	33.93
15	75.28	96.14	.783	28.98
16	59.44	83.74	.710	37.78
17	52.78	74.06	.713	22.01
18	80.43	106.57	.755	31.00
19	62.78	106.56	.589	25.00

May 4, 1987

TABLE 2

REASONS PBAR STACKS WERE DUMPED (includes amount of ma dumped)

Week #	6	7	8	9	10	11	12	13	14	15	16	17	18	19
INCORRECT ARF1 CURVE LOADED	10.8													
A:LQ FAILED		6.95												
TEVATRON FAILURE		3.7												
ESCAPE HATCH BLEW OPEN				11.3										
COMMONWEALTH EDISON GLITCH						26.4								
DEB VAC. VALVES CLOSED (left over from glitch)							5.95							
A:ISEPV,2V REPLACED							2.4							
BLOWN 480 V BREAKER AT AP30							33.3							
SAFTEY SYSTEM ACCIDENTALLY DROPPED							6.5							
M&D									5.35					
D:ISEPV FAILURE											6.1			

Length of Sustained Stacks in the Accumulator

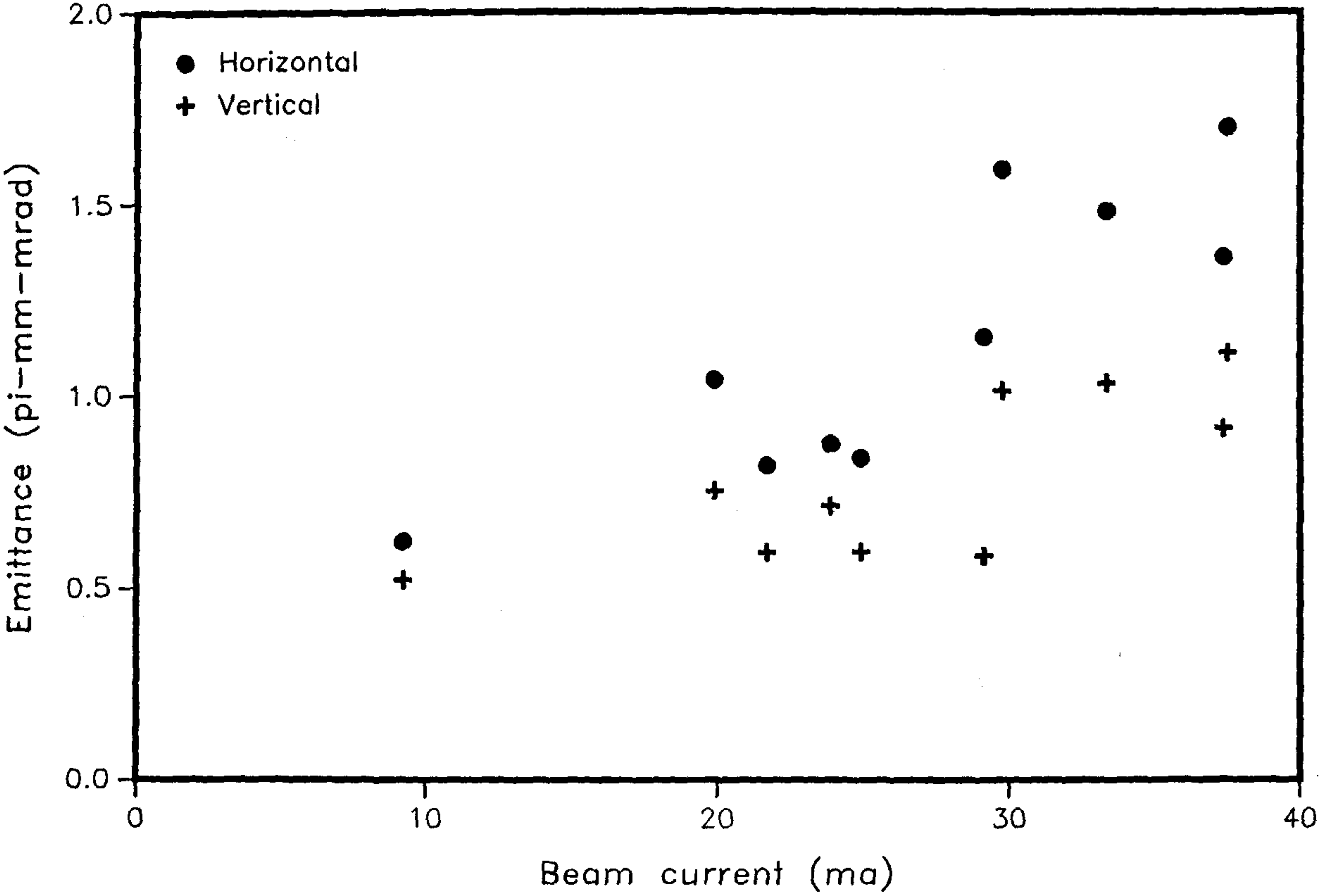
Period	Length (days)
2 Feb - 7 Feb	5.9
7 Feb - 11 Feb	3.1
11 Feb - 13 Feb	2.1
20 Feb - 1 Mar	8.9
1 Mar - 15 Mar	13.5
15 Mar - 22 Mar	6.7
23 Mar - 3 Apr	11.8
4 Apr - 16 Apr	12.4
17 Apr - 11 May	24+ (still in progress)

TABLE 3
PBAR SOURCE STACKING RATE
MISSING FACTOR BREAKDOWN

(UPDATED 4-13-87)

STAGE	DESIGN REPORT	NOV 86	APR 87	MISSING FACTOR APR 87	FACTOR GOAL 87
1. MR INTENSITY ON TARGET	2×10^{12}	8×10^{11}	13×10^{11}	1.54	1.33
2. PBAR PRODUCTION COLLECTION TO DEBUNCHER	7×10^{7}	9.5×10^{6}	14.6×10^{6}	3.11	2.5
3. PBARS AFTER BUNCH ROTATION IN 0.2% $\delta P/P$	7×10^{7}	6.2×10^{6}	12.3×10^{6}	1.19	1.1
4. PBARS IN ACCUMULATOR ON INJECTION ORBIT	7×10^{7}	3.6×10^{6}	10.4×10^{6}	1.18	1.1
5. PBARS ON STACKING ORBIT	7×10^{7}	3.2×10^{6}	9.9×10^{6}	1.05	1.1
6. STACKING EFFICIENCY	80%	100%	88%	0.9	1.0
7. CYCLES/HR	1800	990	1400	1.29	1.5
STACKING RATE (10^{10}/HR)	10	0.316	1.23	8.2	6.7

FIGURE 1


Accumulator Core Emittance

Design is 2 pi-mm-mrad @ 40 ma

FIGURE 2

Accumulator Longitudinal Density

Design density is 6.7x10**10/Hz @ 40 ma

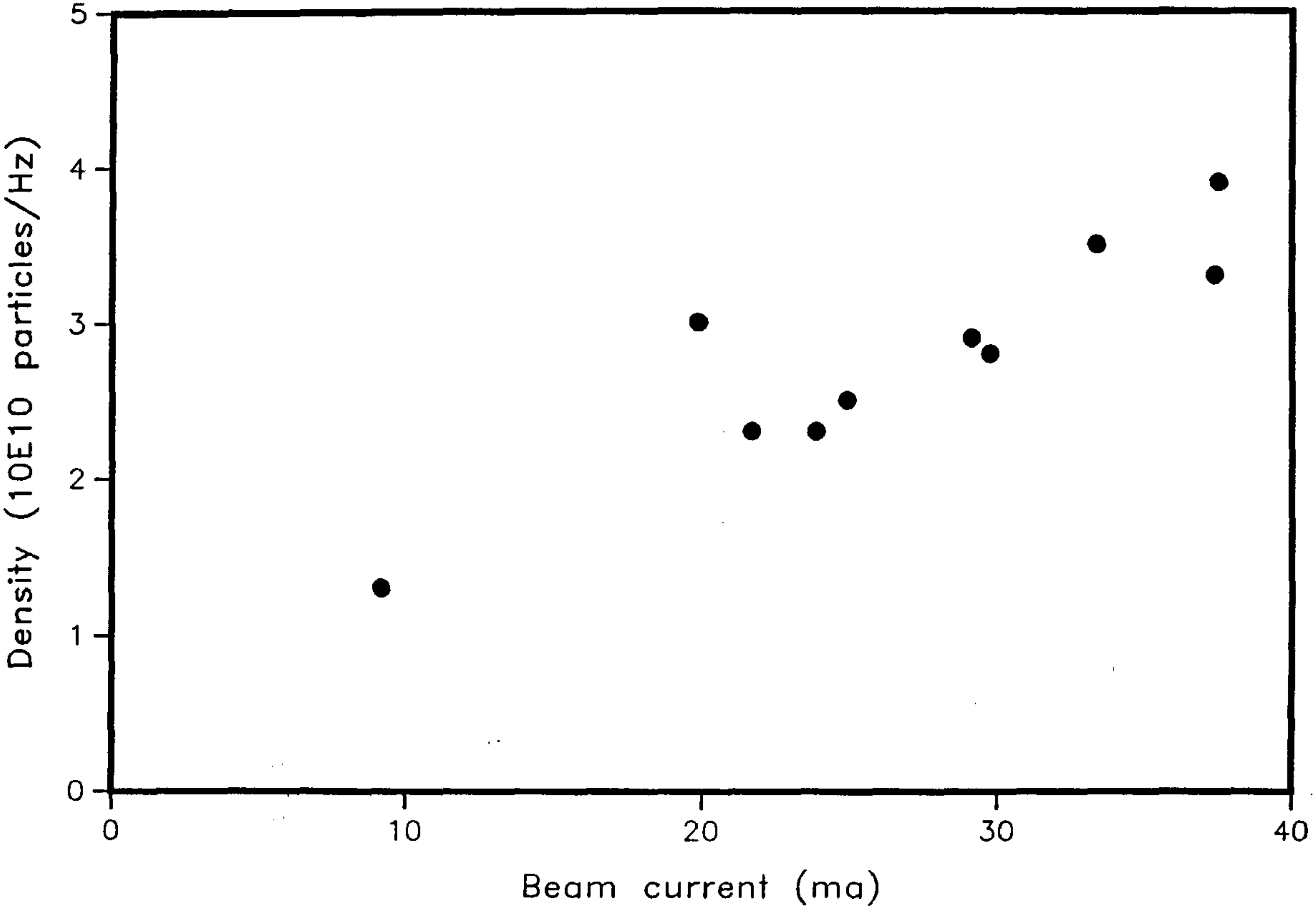


TABLE 4
$\bar{P}$ SOURCE COOLING SYSTEMS
NEAR-TERM UPGRADE

	DEBUNCHER				ACCUMULATOR							
					STACK-TAIL		CORE					
	X(TRANSVERSE)		Y(TRANSVERSE)		LONGITUDINAL		X(TRANSVERSE)		Y(TRANSVERSE)		LONGITUDINA	
	ΔF (GHZ)	P (WATT)	ΔF (GHZ)	P (WATT)	ΔF (GHZ)	P (WATT)	ΔF (GHZ)	P (WATT)	ΔF (GHZ)	P (WATT)	ΔF (GHZ)	P (WAT
PRESENT	2	800	2	800	1	1500	2	10	2	10	2	30
1987-88	2	800^+	2	800^+	1	1500	2	10	2	10	2	30
1988-89	2	1600^+	2	1600^+	1	1500	4	10	4	10	4	30

$^+$WITH OPTICAL NOTCH FILTER

5-1-87

Fixed Target Operation

Mike Harrison
Sam Childress
DOE Review May 87

The upcoming fixed target run will have the following operational characteristics:

Energy = 800 GeV
Cycle time = 57 sec
Slow spill time = 23 sec
3 Fast pulses (~2msec) at 10 sec intervals

During the last fixed target running period (18 months ago), operating under similar conditions we recorded a peak intensity of $1.6*10^{13}$ ppp with an average intensity of $1.25*10^{13}$ ppp. The spill duty factor (uniformity of the slow spill extracted intensity) was typically 90% when analyzed at a rate of 8kHz, and 65% at 53MHz. The overall efficiency of the accelerator complex as defined by the actual hours of HEP running divided by the scheduled hours was ~70% averaged over the whole run, and excluding the first few weeks of start-up.

The quench statistics for the last run show an average of ~1 quench per day, where 30% of these were due to equipment failure (principally caused by spontaneous discharges of the heater firing units in the quench protection system), and 70% that were beam induced. Of the beam induced quenches the vast majority were at low field (150 GeV) where the recovery time is typically 20 minutes, high field quenches, with a recovery time of 1-2 hours, generally occurred during fast spill where the instantaneous beam loss rate into the magnets is 3 - 4 orders of magnitude higher than during slow spill. The average downtime per month due to quench recovery was ~20 hours. Possibly more troublesome from an operational point of view was the number of cycles where the beam was aborted. In order to minimise the number of quenches, beam loss thresholds are applied to the ring-wide loss monitor system, losses greater than these thresholds result firing the abort system. During the fixed target run ~10% of all cycles on average ended in a beam abort. A high percentage of beam abort cycles is generally indicative of equipment malfunctions, beam instabilities, or erratic beam quality from the injector.

Since the last running period the major change in the accelerator complex has been the installation of the B0 overpass in the Main Ring, which has resulted in a somewhat lower beam admittance primarily in the vertical plane. On the positive side, significant improvements have been made in the quality of the beam delivered from the Booster (brighter beams), a totally new 8 GeV injection line between the Booster and the Main Ring has been commisioned, the Main Ring power supply system has been upgraded, oversized magnets have been installed at strategic places in the Main Ring, and we have accumulated, by dint of the collider run, a greater understanding of the beam dynamics in both the Main Ring and the Tevatron. The Tevatron components are effectively unchanged since the last run, though many more beam diagnostics are available this time.

For the next run we believe it may be possible to achieve an intensity of $2*10^{13}$ ppp and have as a goal an average operational intensity of $1.5*10^{13}$ppp. This will require (at least initially) attention being focussed on the Main Ring. Besides raising the overall number of protons available for HEP we will attempt to implement a different operating strategy. In a similar fashion to the recent collider run, we will schedule no regular M&D periods where the accelerator is turned off to allow tunnel access. Experience from the last running period showed that start-ups after an M&D access often took several days to re-establish stable beam conditions and up to a week to optimise beam intensities. It is possible that under this scenario that we may need a week long M&D period several months into the run. We will, however, continue to schedule regular accelerator study sessions on a bi-weekly basis since these are necessary to improve the machine performance. Machine studies have proved to be much less disruptive to the resumption of HEP operation than shutdowns.

For the upcoming run the Switchyard has installed two new electrostatic septa splitting stations, which will provide simultaneous slow spill beam capability for the muon area and the neutrino area NE, and NW beam lines. This completes the upgrade to the planned number of Switchyard primary beam splits, providing simultaneous 23 s spill duration extracted beams to 9 separate lines. Additionally a series of up to eight 2ms fast spill pulses can be delivered during each machine flattop cycle to the neutrino NC line. Beam intensity to each of the slow spill lines can be controlled on request from a minimum of a few times 10^{10} protons/cycle up to the full machine extracted intensity. Also present is the capability to selectively remove beam from any line.

Since the previous fixed target run, a continuing major effort has been devoted to enabling any desired combination of beam splits and beam line status to be achieved quickly, without adverse effect on the adjacent beam lines. During previous Switchyard operation, removing beam from or turning on a high intensity line had a ripple effect throughout the system frequently requiring hours to stabilize. Complete system start-up required a correspondingly longer time period, during which beam conditions were not viable for HEP. A new beam position detector system has been installed throughout the Switchyard beam lines to enable continuous high resolution (0.1mm) measurement at a 10Hz sample rate of beam conditions. Together with new beam trajectory and splitting control capability, major improvements are expected in reduced set up times, beam stability, and beam split control.

The long term goals of the fixed target program involves raising both the beam energy and intensity. The present limitation to the beam energy is the ability of the Tevatron magnets to tolerate the fast spill beam losses. At a 900 GeV excitation level the magnets will quench much more easily than at 800 GeV, and preliminary data obtained during the collider run indicates that we would exceed the 900 GeV quench levels by a factor of ~20, and possibly more, under identical running conditions. Increasing the fast spill energy would require lower temperature operation of the magnets to provide a similar tolerance to beam loading as in 800 GeV operation. Slow spill beam energy could be increased under the present enviroment though the determination of a safe operating energy would require several days of studies. All Switchyard Cryogenic and beam transport systems have been successfully tested to levels corresponding to 1 TeV operation.

The Tevatron at 800 GeV appears to be capable of extracting at least a factor of two more intensity than we have achieved so far, sources of concern would be injecting and accelerating intensities of $\sim 3*10^{13}$. The Tevatron injection aperture is large enough to accomodate the presumably bigger beams which one expects in this situation. Significantly denser phase space beams present possible beam instability problems though the threshold for these effects is unknown at present. Greater intensity would also allow the flattop time to be increased while maintaining a constant spill rate thus providing an increase in the effective duty cycle. A factor of two increase in the extracted beam intensity poses no problems in the Switchyard.

During the upcoming run, R & D efforts in the Switchyard to produce still higher resolution beam position detectors for each septa station will be on going. The goal is maintaining the 0.1mm resolution with sampling rates sufficiently fast to be sensitive to power supply ripple effects, which at times produce large modulations in split beam intensities. Another on going Switchyard R & D effort is aimed at having most diagnostic, set-up, and control systems capable of taking advantage of the essentially DC character of the Tevatron slow spill. The goal is to allow multistep data collection and control operations to be completed during a single machine cycle, rather than the current system of collecting a single data point per cycle. This would compress the time needed from hours to a few machine cycles for many operations presently destructive to HEP.

Tevatron replacements and spares

During the past year the Tevatron was operating for approximately 8 months in start-up and collider running. During this 8 month period a total of 23 cold elements were replaced in the tunnel. The component breakdown was as follows:

8 TB dipoles
7 TC dipoles
4 quadrupoles
2 spoolpieces
1 feedcan
1 warm bypass

The reasons for these failues were:

14 bad vacuum (1f, 2f, N_2 leaks)
1 low quench current
4 electrical failure (1 shorted, 1 open, 1 bad splice joint, 1 broken leads)
1 mechanical failure (cracked flange)
2 magnetic field matching (good magnets with field quality incompatable with adjacent replacement)
1 insufficient power lead cooling

The large number of component failures due to leaks of one sort or another is attributed to the thermal cycling of the elements during the start-up period since all the system had been warmed up to room temperature during the 12 month shutdown. Since the scheduled start of the collider run on 15 Jan there have only been two failures of cryogenic components which required a warm-up. Only two Main Ring magnets were changed in this period, one due to a vacuum leak the other with bad voltage-to-ground characteristics.

TEVATRON CRYOGENIC RELIABILITY AND CAPACITY UPGRADE: STATUS

W.B. Fowler, T.J. Peterson, J.N. Makara
May 1, 1987

OPERATIONS TO CURRENT DATE

The cryogenic downtime to current date is shown in Figure 1. The refrigeration downtime is split between the Central Helium Liquefier (CHL) and the ring cryogenics. The quench recovery time includes power supply and beam restart.

The primary cause of downtime now and in the past is contamination. In the past it caused more than half of the CHL downtime and was the largest cause of Satellite downtime. By reducing CHL capacity, plugging CHL dewar lines and plugging Transfer Line valves, it also increases quench recovery time. During this past running period, CHL has scheduled their derime of plugged filters during scheduled accelerator maintenance periods, thus not generating official downtime. Current satellite downtime is most significant in power lead cooling flow problems (compensated with increased flow, thus greater CHL load) and weak refrigeration due to engine failure, vacuum problems, or transients (also corrected with greater CHL flow).

The second most significant downtime item was a CHL compressor water leak in 1985 which shut down the Tevatron for eight days. This demonstrates how vulnerable we are to CHL major component failures.

The remaining items relate to the failures of individual parts: Electronic circuits, transducers, O-rings, etc. This will continue to require a continuous effort on maintenance and improvements, including some re-design of electrical circuits and control circuit boards.

Table I shows the hours of downtime for the 15 most troublesome systems during the 1985 running period and Table II shows current year operations. (We were shutdown from October, 1985, to October, 1986.) In Table I from the top, ordered by percentage down time, items four and five are cryogenics. The top three, while not caused by cryogenics, are strongly affected by the ability of the cryogenic system to cooldown and fill the magnets i.e. peak capacity. For example, UPOWER, site power, is large because a one hour site power outage generates about thirty hours of downtime due to the refill time of the magnets. Recent operations show improvement due to CHL dewar/LHe pump system providing backup during CHL crashes.

REDUNDANT CENTRAL HELIUM LIQUEFIER

While we will continue to improve the Satellite reliability by weeding out weak components and poor designs, the major reduction in downtime will be achieved by a $2.3M capital equipment expenditure for the CHL upgrade. There are 4 parts to this upgrade:

1. Subsystem Independence.
2. Redundant Liquefier.
3. Increased Peak Capacity
4. Increased steady-state capacity

The first is the most important aspect of the upgrade; if one CHL subsystem fails it must not keep others from functioning. Figure 2 is a highly over simplified schematic showing the subsystems. The distribution box contains a 10,000 liter/hr subcooler and nine Helium U-tubes for isolation between components. In addition to the U-tubes, isolation valves inside the box allow various modes of operations if maintenance on individual components is required. The past shutdown has allowed us to install such equipment for the first coldbox and provisions to add the second coldbox/distribution/compressor system, while the first is online and operating.

The second item should be started as soon as money is available but can be accomplished with the accelerator operating, assuming the first item is complete. A failure mode analysis of the CHL shows that there is a need for a second cold box, since recovery from a failure of the existing cold box could exceed two months, thereby stopping all high energy physics at Fermilab. As figure 2 shows the second cold box will be configured in a parallel system to the present CHL plant, with redundant purification systems, oil removal systems, distribution boxes and helium pumps. Thus, the plant operation will be protected from not only catastrophic failure of the cold box but the more standard failures associated with contamination or failure of pumps and turbines. A fourth compressor will be reconditioned and added in parallel with the three presently operating compressors. The program has been reviewed and is oriented to minimize the exposure to catastrophic failures of CHL. Equipment which would aid in recovery from major component defects has been given priority and will be procured first.

Priority will be put on procurement of a fully redundant cold box, and the components necessary to connect that cold box to the operating system, in case of failure. Second priority will be given to the development of the complete parallel system, and then to the fourth compressor rebuilding. The fourth compressor aids in establishing independence of the two CHL cold boxes. This means that a pretested backup will always be available and sufficient independence will allow repair and check-out of the failed component without interference with Tevatron operations.

The third item, increased peak capacity, has been implemented. Improvements have been made on the two dewars, liquid pump, and dewar transfer lines thus enabling us to provide ~6000 liters/hr of liquid He capacity. This significantly improved the ability to quickly recover from quenches. Minor CHL coldbox or compressor trips during the recent operations have had little impact on ring operations when the dewar/pump system was online as back-up (see Figure 1).

With the improvements of the liquid storage system we also can significantly reduce the downtime effect of power outages. The pump/dewar system should be able to be restarted in a matter of one or two minutes. Time wise the best restart of CHL to date has taken 1.5 hours. We would hope that after a one hour power outage we could have the Accelerator back up in less than 12 hours.

The fourth item, increased steady-state capacity, is required for the increased demand which may result from D0 low-beta, an upgraded B0 low-beta, and lower Tevatron temperature for 1 TeV operations. Also, weaknesses in the satellite system are often temporarily compensated with increased CHL demand thus allowing more failures to accumulate before requiring downtime for repairs. The new coldbox and turbo-expanders will provide 7000 liter/hr instead of the 5000 liter/hr of the existing system.

TEVATRON CRYOGENICS IMPROVEMENTS

Power lead failures have generated a good deal of downtime due to the requirement of tunnel access for repairs or adjustments. New lead designs are being incorporated in new components (D0, B0 Low Beta's) and a better flow control system is planned for all Tevatron power leads. A scheme for preventing frozen water lines on leads during maintenance periods or during no-power periods is being worked on.

Figure 3 shows the cryogen consumption for the past two running periods. Helium losses are continuously being monitored and some improvement is seen as operations continue. Work is in progress to improve detection and correction of helium leaks after quenches, compressor failures, leaking valve seals, or other operational malfunctions. Production of R. Walker's helium leak detection (based on density difference with surrounding environment) is in progress. Rewrite of the helium inventory program and training of CHL personnel to assist on satellite refrigerator relief system repairs will be undertaken in the near future.

The nitrogen reliquifier (NRL) has been operational for the past five months with few difficulties. Continuous tuning of LN_2 usage needs greater attention. NRL reliability should improve with modifications to the water cooling system, upgrade of control software, and operator training. The vast amount of current LN_2 storage allows continuous supply of liquid nitrogen to both CHL coldbox and ring even during NRL crashes.

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DOWNTIME DURING SCHEDULED OPERATION
('85-PRESENT)

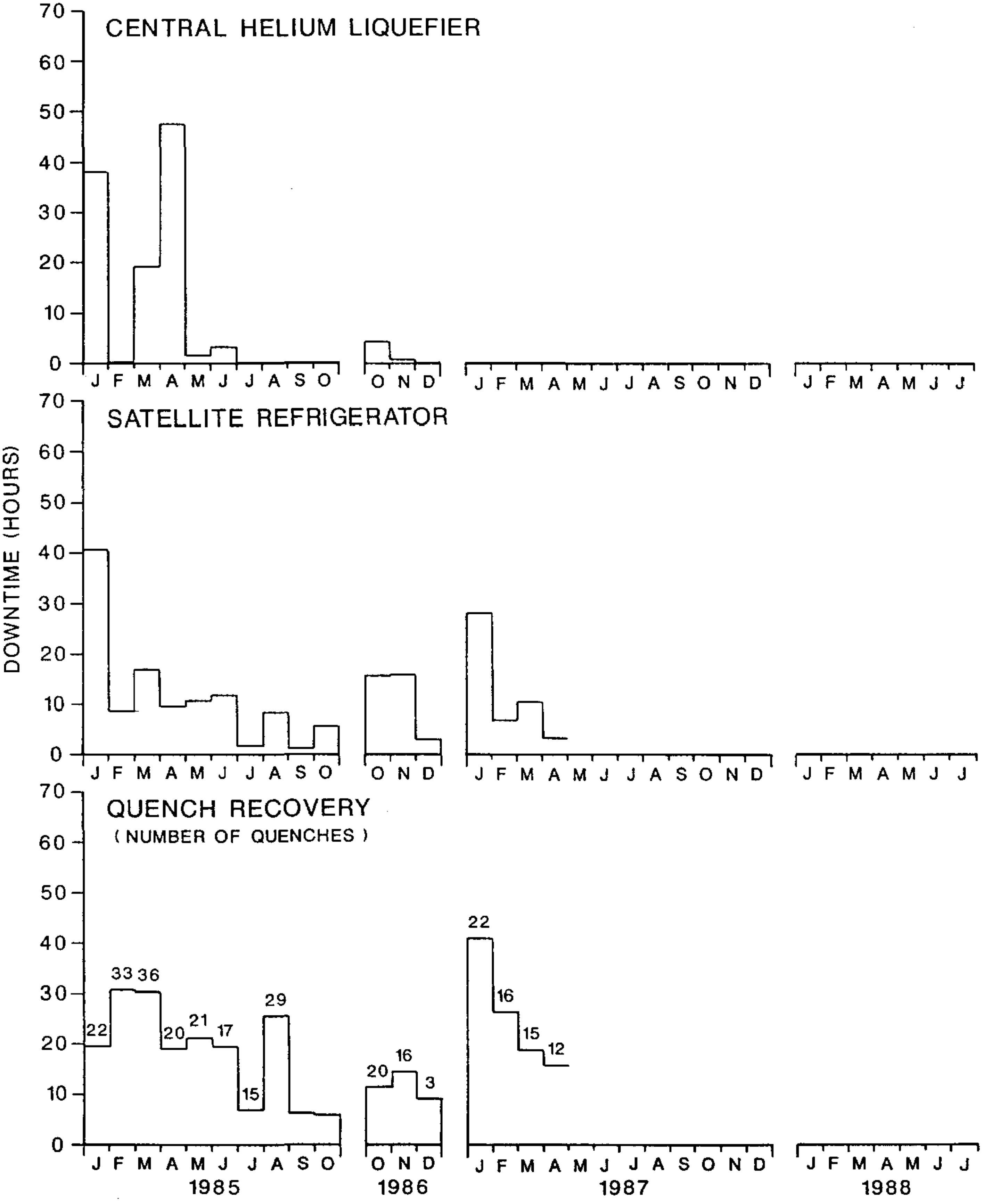

FIGURE 1

MAJOR ACCELERATOR DOWNTIME 1985

	SYSTEM	HOURS	%	ENTRIES	SYSTEM DESCRIPTION
1	UPOWER	181.09	8.1	41	Site Electrical Power
2	TQUEN	165.06	7.3	164	Quench Recovery
3	TMAG	156.05	6.9	14	Tevatron Magnet
4	TCRYO	119.05	5.3	285	Satellite Refrigerator System
5	UCHL	108.05	4.8	53	Central Helium Liquefier
6	TPS	108.02	4.8	111	Tevatron Power Supplies
7	TQPM	108.00	4.8	164	Quench Protection Monitors
8	LRF	104.08	4.6	535	Linac RF
9	MRMAG	97.84	4.3	13	Conventional Magnet
10	MRPS	97.03	4.3	177	Conventional Accel. Power Supplies
11	MRMISC	84.79	3.8	73	Conventional Accel. Misc.
12	TMISC	76.44	3.4	210	Tevatron Accel. Misc.
13	MRREG	59.58	2.6	130	Conventional Accel. Regulation
14	SYPS	51.55	2.3	181	Switchyard Power Supplies
15	TCOR	51.16	2.3	113	Correction Magnets
TOTAL	DOWNTIME	2255	100	4126	Overlapping Downtime Included

Table I

jp

MAJOR ACCELERATOR DOWNTIME 1986 - 1987

	SYSTEM	HOURS	%	ENTRIES	SYSTEM DESCRIPTION
1	TQUEN	137.5	9.0	104	Quench Recovery
2	TMAG	99.6	6.5	8	Tevatron Magnet
3	CMISC	93.8	6.1	494	Controls Misc.
4	TCRYO	82.7	5.4	68	Satellite Refrigerator System
5	TPS	55.7	3.6	49	Tevatron Power Supply
6	MRPS	52.1	3.4	128	Conventional Accel. Power Supplies
7	LRF	52.1	3.4	332	Linac RF
8	MRMISC	48.3	3.2	63	Conventional Accel. Misc.
9	TVAC	46.9	3.1	46	Tevaron Vacuum
10	APPS	46.2	3.0	48	Anti-proton Power Supply
11	TCOR	40.4	2.6	42	Tevatron Correction Magnets
12	UPOWER	39.1	2.6	11	Site Electrical Power
13	TMIS	33.8	2.2	42	Tevatron Accel. Misc.
14	MRREG	31.5	2.1	56	Conventional Accel. Regulation
15	TCOR	30.5	2.0	38	Tevatron Controls
TOTAL DOWNTIME		1529.4	100	2398	Overlapping Downtime Included
Calendar Time		5088.0	30.1		Calendar % Downtime

Table II

jp

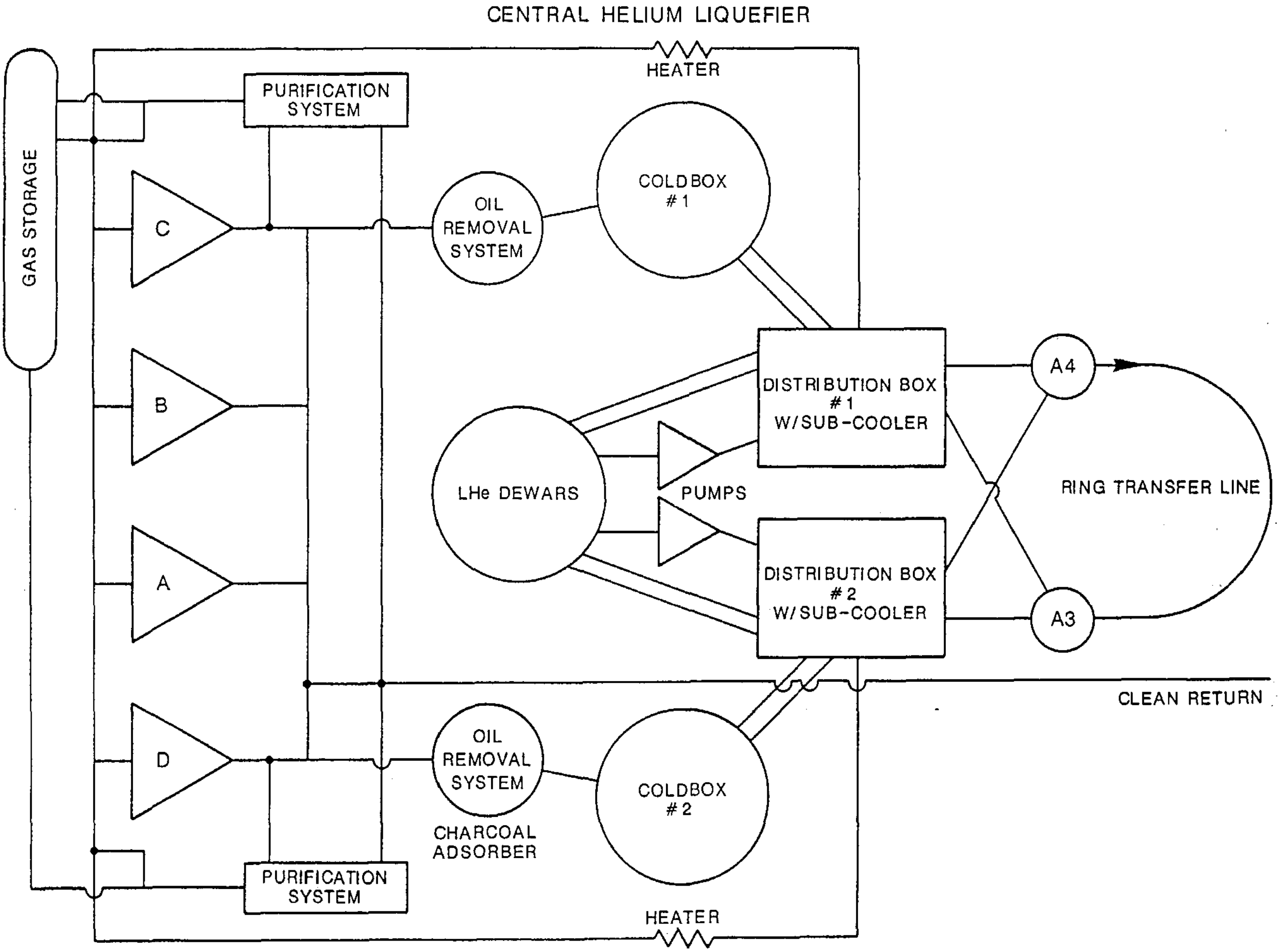
CENTRAL HELIUM LIQUEFIER
HEATER
GAS STORAGE
PURIFICATION SYSTEM
C
B
A
D
OIL REMOVAL SYSTEM
COLDBOX # 1
DISTRIBUTION BOX # 1 W/SUB-COOLER
LHe DEWARS
PUMPS
DISTRIBUTION BOX # 2 W/SUB-COOLER
A4
A3
RING TRANSFER LINE
CLEAN RETURN
OIL REMOVAL SYSTEM
CHARCOAL ADSORBER
COLDBOX # 2
PURIFICATION SYSTEM
HEATER

FIGURE 2

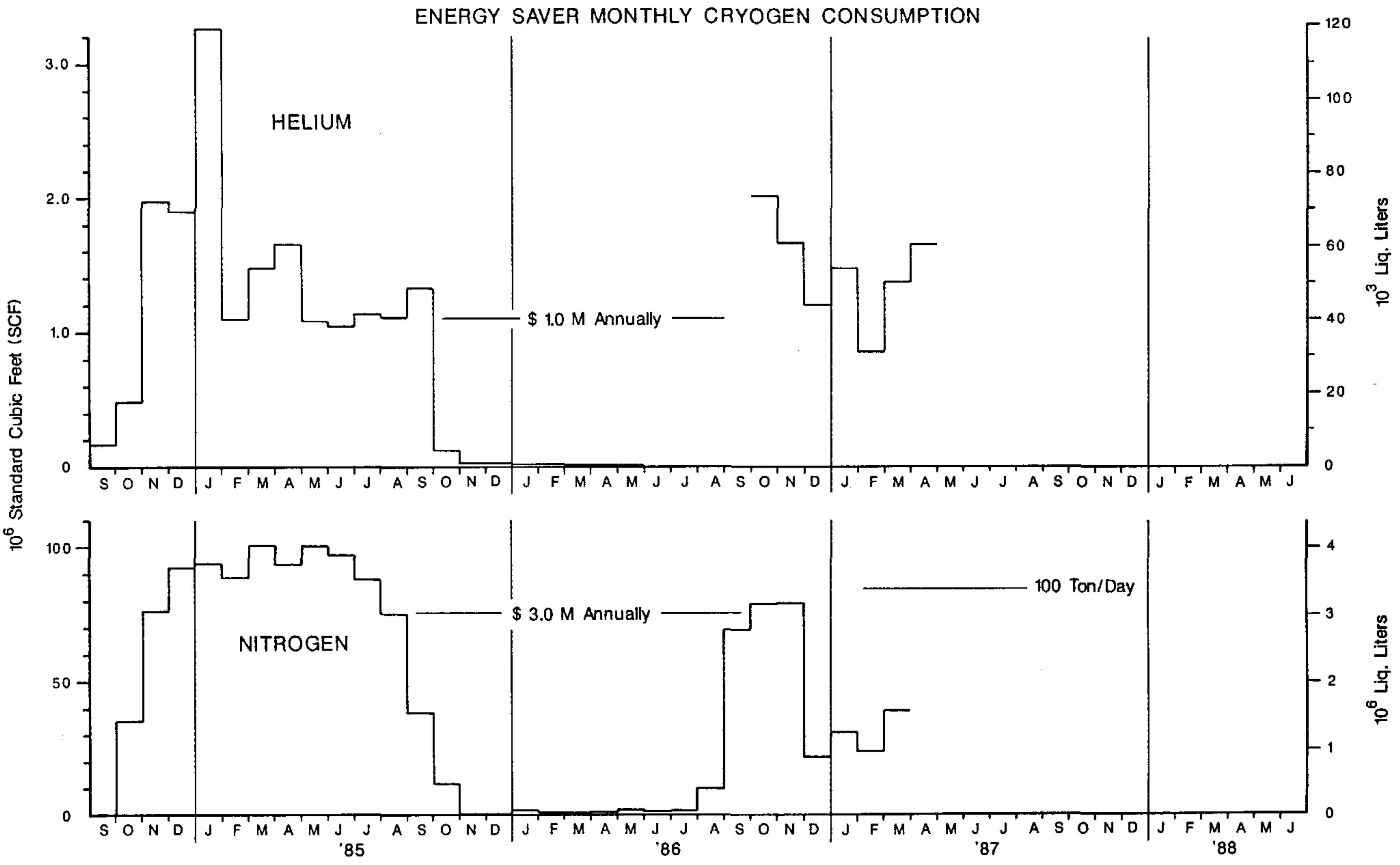
ENERGY SAVER MONTHLY CRYOGEN CONSUMPTION
HELIUM
$ 1.0 M Annually
NITROGEN
$ 3.0 M Annually
100 Ton/Day
10^6 Standard Cubic Feet (SCF)
10^3 Liq. Liters
10^6 Liq. Liters
3.0
2.0
1.0
0
100
50
0
120
100
80
60
40
20
0
4
3
2
1
0
S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J
'85
'86
'87
'88

FIGURE 3

TEVATRON ENERGY UPGRADE: PROGRESS AND PLANS

Tom Peterson
April 29, 1987

INTRODUCTION AND SUMMARY

During commissioning of the Tevatron the machine energy was limited to 800 GeV. This was due to some magnets quenching at the higher currents required for higher energy. Previous reports have described a plan to achieve 1 TeV based on a combination of magnet replacements and lower temperature operation of the superconducting magnets using cold compressors. Proposed magnet replacements were completed during the year-long shut-down which began in October 1985. Cold compressor R & D has begun, and refrigerator studies have been carried out using computer simulation programs. We now believe that we adequately understand our present limits and are able to appropriately assess limits for lower temperature operation.

In summary, 1 TeV operation of the Tevatron for P-BAR, P colliding beam experiments is achievable by changing the cryogenic system from 1.23 atm suction pressure to 0.7. This change lowers the operating temperature of the superconductor such that higher magnetic fields are possible. This upgrade requires cold compressors at each of the 24 satellite refrigerators. Tests of cold compressors have shown that continued testing and development will be required before any cold compressor is proven suitable for our application. These components constitute the major cost. The estimated total hardware cost is $2,400,000 including an approximate 15% contingency allowance. A 2 1/2 year time estimate is judged appropriate.

MAGNET REPLACEMENTS

During September, 1985, after repairing some poor splices and replacing some known weak magnets, each of the six sectors was successfully ramped to 920 GeV equivalent. During the 1986 shutdown about 15 dipoles were replaced based on low-current quenches in Magnet Test Facility data. We have met our short-term goal of 900 GeV collider physics during the past six-month run.

RESULTS OF REFRIGERATOR CALCULATIONS-DESIGN FOR 1 TeV

In collider mode our satellite refrigerator heat load is estimated to be 560 Watts (70W static heat load per half-cell). This is to be compared to approximately 800W per refrigerator for our 800 GeV fixed target run during 1985. This indicates, as our simulations have confirmed, that our satellite refrigeration system presently has the capacity to handle the additional heat load of cold compressors running with a 0.7 atmosphere inlet pressure, a temperature decrease sufficient for a 100 GeV upgrade. A 100 GeV upgrade will give us 1 TeV.

COLD COMPRESSOR R & D

During January, 1986, a turbine-type cold compressor developed for Isabelle (CBA) string tests by Creare, Inc., was tested at our BR satellite refrigerator with a dewar and heater as a load. Flow and efficiency were measured for a variety of conditions. Efficiency was low (less than 50%), as expected since we were running under conditions far different from those for which the compressor wheel was designed.

During September, 1986, the same Creare cold compressor with a wheel designed for 1.0 atmosphere helium inlet conditions was tested at our ER refrigerator. It attained 60% efficiency, what we have chosen as satisfactory, at its design conditions and flow rate. But it still needs to be tested with the 0.7 atmosphere inlet pressure that calculations indicate is required for a 1 TeV upgrade.

A reciprocating-type cold compressor from CCI was tested extensively from October, 1986, through January, 1987. After some modifications it attained 50% efficiency for 1.0 atmosphere helium inlet conditions and the flow rate required for operation with a satellite refrigerator. For 0.7 atmosphere inlet conditions at the required flow rate the cold compressor speed would be nearly the maximum for the machine. Mechanical reliability under those conditions still needs to be proven.

Tests of the Creare cold compressor with subatmospheric inlet pressures are planned for June, 1987, and further CCI cold compressor tests are also planned. Neither unit has yet been proven capable of meeting the requirements for a cold compressor that would provide a 1 TeV upgrade.

We also must prove that we can tighten-up the two-phase side of our system for subatmospheric operation. If subatmospheric operation does prove to be too unreliable in tests, the cold compressor and associated hardware can be operated at 1.0 atmosphere as a fallback position (a specification for cold compressor will require this), but the accelerator would have to operate at less than 1 TeV (i.e., about 950 GeV).

Clearly, a considerable R & D effort is required before we can have 24 cold compressors operating reliably in the Tevatron refrigeration system. This development effort should be staged. A possible program is outlined below.

Remainder of FY87:

Test Creare and CCI cold compressors extensively at ER under full flow, 0.7

atmosphere inlet pressure operating conditions.

FY88

1. Upgrade one magnet system for subatmospheric operation (November, 1987). Install the preferred cold compressor and test subatmospheric operations at one refrigerator.
2. Purchase three more cold compressors. Upgrade the other three refrigerators and magnet strings in that sector. Power test that sector to 4440 Amps (1 TeV equivalent).

FY 89

Purchase balance of cold compressors and other required hardware and controls. Begin installation.

FY 90

Begin 1 TeV collider operations.

COST ESTIMATE FOR 100 GeV UPGRADE

	One Refrigerator	24 Refrigerators
Cold Compressor	$60,000	$1,440,000
Seal Upgrade	$10,000	$ 240,000
Controls and Instrumentation	$15,000	$ 360,000
U-Tubes	$ 2,000	$ 48,000
Contingency @~15%	------	$ 312,000
Total	$87,000	$2,400,000

POSSIBLE BUDGET (in $1,000 units)

	FY87	FY88	FY89
R & D	75	75	---
24 units with associated parts and work		348*	1740
		(one sector)	(five sectors)

* It is unlikely these funds will be available in FY88.

Conclusion

Over the next 2 1/2 years, for about $2.4M we can lower Tevatron temperature sufficiently for a 100 GeV upgrade, from 900 GeV to 1 TeV, provided the following occur:

1. Tests prove the available cold compressors to be thermodynamically adequate and mechanically reliable. This must still be proven since cold compressors so far do not have operating histories; they are new technology. Both cold compressors tested so far still require some testing and development work.

2. We must make the 2-phase side of our cryogenic system leak tight. Seals to air will be double seals with helium in between. Subatmospheric systems using this procedure operate reliably.

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STATUS OF THE D0 LOW BETA INSERTION

Ernest Malamud

May 1, 1987

One measure of the efficiency of exploiting the Tevatron Collider for physics is the number of collisions that occur during a given running period. This number is proportional to the integrated luminosity at each major detector. As the luminosity is raised, the likelihood of detecting collisions of a quark and antiquark which contain large total energy is increased, creating opportunities for new physics discoveries.

The luminosity for head-on collisions is given by:

$$L = N_p\, N_{\bar{p}}\, B\, f_o / \, 4\pi\sigma^2,$$

where N_p and $N_{\bar{p}}$ are the per bunch intensities, B is the number of bunches in each beam, f_o is the revolution frequency (47 kHz) and σ is the rms beam size of either beam. Round beams are assumed and this formula is uncorrected for the variation of beam size through the interaction region. Thus the luminosity is approximately inversely proportional to the area of the proton and antiproton beams at the collision point. For a given emittance beam, the transverse beam size can be obtained from the function, β. If β at the intersection point, called β^*, is reduced a factor of two in each plane, the beam size is reduced both horizontally and vertically by $\sqrt{2}$ and a factor of two increase in luminosity is obtained.

The currently installed and successful low-β insertion at B0 operates at a nominal β^* of 1 m. In fact, during the current run β^* has been made as low as 85 cm by operating the existing insertion in a "mini-β" mode. There is no low-β insertion at D0, and one must be constructed for the experimental program in the large detector being built there. At D0 the goal will be to build and install an insertion in time for the first run of the D0 detector in 1989 that can reach values of $\beta^* < 50$ cm.

β^* can be made smaller by using stronger low-β quadrupoles or moving them closer to the interaction point. However, the latter approach is limited by the goal of making the detector as hermetic as possible and covering the small angle region where momenta are higher and require more room for particle measurements. As β^* is reduced, the maximum value of the amplitude function, β_{max} increases. It is important that β_{max} not become too large and make a beam admittance restriction that would reduce the lifetime.

A conceptual design for the D0 insertion has been developed. It requires the addition of arc-matching correction quadrupoles to match the betatron lattice functions between the arcs and the straight sections. Still under consideration are various schemes which reduce the dispersion mismatch in the Tevatron ring. A matched insertion design can be replicated at other straight sections. The present plan is to do this at B0, replacing the existing insertion, and thus approximately doubling the number of collisions per year that the powerful CDF detector can study. One can also consider a third, identical low β insertion at another of the 6 long straight sections. Going from one major detector operating with a β^* of 1 m to three major detectors each operating at a β^* of 50 cm means that 6 times more collisions per year can be studied in the Tevatron Collider physics program.

The insertion being built for D0 uses five pairs of quadrupoles. The longest is 252 inches, and the shortest is 60 inches. One of these pairs is required to operate at gradients of 1.9 Tesla/cm. The three pairs bracketing the detector form asymmetric triplet lenses. The elements in the triplet operate at maximum gradients of 1.4 T/cm. The fifth pair of quadrupoles are normal lattice quadrupoles separately powered from the ring. When the high gradient pair runs at 1.9 T/cm, a β^* at 1 TeV of 18 cm is attained. β_{max} is kept less than 1800 meters. These, of course, are the operational limits.

The present low-β warm iron quadrupoles at B0 perform at 1.12 Tesla/cm. A final design has been made for a cold iron, two-shell quadrupole that operates at 1.8°K and provides the required gradient of 1.9 T/cm at a current of 7000 amps. At 4.7° K, 1.4 T/cm can be reached with the same magnet cross section. The design still allows operation with all 4 quadrupole pairs at 4.7°K and maximum gradients of 1.4 T/cm. In this case β^* will be about 40 cm.

The inside coil diameter is 3" and there is a clear beam aperture of 2.4", equal to the horizontal and vertical Tevatron dipole aperture. The outside of the cold iron is 12" in diameter. Design of 1 meter long prototype coils, coil curing fixtures, coil collars, and collar assembly tools is nearing completion. During May and June prototype components will be built. The schedule calls for the first prototype to be ready for tests in a vertical dewar in September and the first complete quadrupole to be ready April, 1988. Ways are being explored to compress the schedule so that all the quadrupoles needed for the D0 insertion are on hand before the end of 1988.

Initial models and prototypes will use NbTi material. NbTi will be used in the triplet lens quadrupoles running at 1.4 T/cm, and NbTiTa material, which has superior characteristics at superfluid temperature, will be used in the 1.9 T/cm quadrupoles. Both the NbTi and NbTiTa materials have been ordered. The superconducting cable will be woven from .020" strand containing 630 filaments, 13 microns in diameter and a copper to superconducting ratio of 1.5:1. It is expected that the NbTi can reach a current density of 3000 A/mm^2 at 4.6° K and 5 T, and the ternary material can reach the same current density at 1.8° K and 8 T. There are 47 turns per pole in the final two-shell design.

The D0 low-β insertion also requires considerable electrical, cryogenic, and mechanical design and engineering effort. One of the magnet facility test stands will be modified for 1.8° K operation. Although the insertion at D0 will be built before the retrofit at B0, an attempt is being made to keep them identical to reduce spares requirements. The innermost quadrupole of the triplet is cantilevered into the collision hall and inserts into the end caps of the major detectors. The CDF detector presents the more restrictive constraint; it requires that the cryostat fit inside an 18" square, whereas the constraint at D0 is a 22" square. A preliminary cryostat design satisfying this constraint has been made. Heat loads have been calculated and a decision made to operate the D0 low-β quadrupoles on the existing refrigerators in the C4 and D1 service buildings. The higher gradient pair of quadrupoles require a separate 1.8° K refrigerator to achieve their maximum design gradients.

The D0 low-β insertion is mechanically more complex than either the present one at B0 or the retrofit planned for B0. Since the electrostatic septa for extracting the proton beam from the Tevatron are located at D0, this straight section must be reconfigured each time the physics program is switched between fixed target and collider mode. Mechanical designs have been made for mounting sets of components on movable girders to make these changeovers efficient and reproducible.

Since operation of a superconducting quadrupole with superfluid helium will be in a new regime, it is not known exactly how rapidly quenches will propogate. Quench propagation velocities will be measured, and the quench protection equipment designed, constructed and tested.

Related to the increases in quadrupole gradient is the development of special higher field superconducting dipoles. An increase in luminosity can also be gained by increasing the number of bunches in the ring. However, this scheme requires that the number of collision points be kept to a minimum. Electrostatic separators keep the two beams apart except where detectors can observe collisions. The optimum location of the separators may require making additional space in the Tevatron lattice. Special dipoles that have 4/3 of the magnetic field of the present Tevatron magnets (i.e. 6 T) and run in series with them can be developed. Having such magnets available allows great flexibility in adding new devices into the lattice, such as the separators or kickers.

1.8K and 4.7K REFRIGERATION FOR LOW-β QUADRUPOLES

Tom Peterson
April 29, 1987

INTRODUCTION

The design for low-β cryogenics has changed significantly since the July 8, 1986, report was written. Only one magnet (called QI-1) on each side of the interaction region will be at 1.8K. The others will be at 4.7K.

USE OF THE EXISTING SATELLITE REFRIGERATORS AND CHL

The facts that most of the magnets will be at 4.7K and that they will be cold iron, low heat-leak magnets allow them to be added to the existing C4 and D1 satellite refrigerators. Our presently operating B0 low-beta system was added to the existing satellite refrigerators on each side of B0. If the new D0 low beta magnets and associated components can be designed to add less heat to the helium system than the B0 low-beta magnets (about 100 watts at 4.7K per satellite refrigerator), then additional helium refrigeration capacity for D0 low-beta will not be necessary. The use of cold-iron magnets and SSC-style support posts should result in such a low heat load.

About 5% of the "single-phase" (4.7K, 2 atm) helium will be tapped off and further cooled to 1.8K to cool the QI-1 quadrupole. Such a low temperature will require continuously pumping a bath of liquid helium to a pressure of about 0.016 atmospheres. Other methods could be developed for cooling helium to such low temperatures, with the advantage of eliminating the low pressure helium pumping and its danger of air leaking in, but considerable R & D might be required. Even the more conventional vacuum pumping technique will require a significant design effort. As a fall-back position the QI-1 quadrupole can be operated at 4.7K, providing a β^* of 40 cm rather than 18 cm.

A SUPERFLUID MAGNET TEST STAND

For testing the QI-1 magnet at 1.8K (helium becomes superfluid below 2.17K) a special test stand has been designed and is being constructed. It incorporates a vacuum pumping system and other special components for making and handling superfluid which will also be required in the QI-1 magnet cooling system. Thus, the test stand both serves to test prototype superfluid components and the low-beta magnets. Other proposals for 1.8K accelerator magnet systems, such as "Preliminary Study of a Superfluid Helium Cryogenic System for the Large Hadron Collder", by G. Claudet, et. al., and the possibility of avoiding "training" quenches in SSC magnets by conditioning them in superfluid helium make this superfluid test stand and the proposed operation of QI-1 in superfluid significant developments for the accelerator community.

IMPACT ON CHL

Although the heat leaking in via the magnets and other components is being designed to be small enough to add to the existing satellite refrigerators, the additional liquid required by the power leads and superfluid magnet will significantly add to the demand on CHL. D0 low-beta requires five separately powered quadrupoles on each side of the interaction region. This results in a total of twenty vapor-cooled current leads. These twenty leads and the vacuum pumps producing superfluid will consume an additional 375 liters per hour of liquid helium from CHL via our liquid helium transfer line, an increase of about 10%. The increased CHL capacity provided by operating the second coldbox with its higher capacity Rotoflow turbines will satisfy this increased demand for liquid helium.

SUMMARY

The D0 low-beta cryogenic system as presently planned includes both cold-iron, low heat-leak 4.7K quadrupole magnets cooled by the existing satellite refrigerators and magnets cooled with superfluid helium which is produced by locally cooling some of the 4.7K satellite refrigerator flow to 1.8K in special subcoolers. The additional liquid demanded for power leads and the production of superfluid can be provided by the second, higher-capacity, CHL coldbox. A 1.8K test stand will provide both a test facility for the low-temperature magnets and information regarding the design and performance of the special components required for producing and handling superfluid. Worldwide interest in the operation of accelerator magnets in superfluid give this project special significance.

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Progress and Plans for the Linac and Booster

D. Young & S. Holmes

May 4, 1987

Improvements in the Linac and Booster accelerators are in progress and gains have been realized during the last year. The improvement program in the Linac consists of work in two areas. The first is the Linac Upgrade which requires the replacement of the last four drift-tube cavities (with an energy of 116 to 200 MeV) with more efficient, higher gradient cavities so as to increase the energy of the Linac to 400 MeV in the same available length. The increased Linac energy will require minor modifications in the Linac diagnostic area, the beam transport line to the Booster, and injection into the Booster to accommodate the higher energy. A conceptual design has been completed and construction funds have been requested for FY89.

Increasing the energy of the linac from 200 to 400 MeV involves a reexamination of the most suitable accelerating structure for this application. It is required that the accelerating gradient be increased from 2.5 MV/m to 7.5 MV/m to achieve acceleration to 400 MeV in the same length as the old accelerating cavities. To be able to withstand the higher voltage gradients requires that the frequency be increased; the breakdown voltage scales as the square root of the frequency. 800 MHz is a good choice and this frequency also allows the 200 MHz beam bunches to be captured in the higher frequency buckets. A suitable accelerating structure might well be the side-coupled structure developed at LANL in the early 1960's for the Los Alamos Meson Factory. However, another possibility for an accelerating structure is the Disk-And-Washer (DAW) structure which has been used in the USSR. The outstanding features of the DAW structure are the high efficiency for rf acceleration, the high stability resulting from the large coupling between cells, good vacuum properties, and possibly simpler fabrication resulting from the reduced mechanical tolerances. Presently this structure is being evaluated by computer and low-power frequency modelling and testing. A next step in the evaluation of either the DAW or the side-coupled structure is a test at full power to evaluate the difficulty of achieving the required accelerating gradient. Neither of these structures have been tested at a gradient of 7 to 8 MV/m. To do these tests a 1 MW, 800 MHz power supply will be required. It is planned to start on the design and procurement of this equipment as soon as possible.

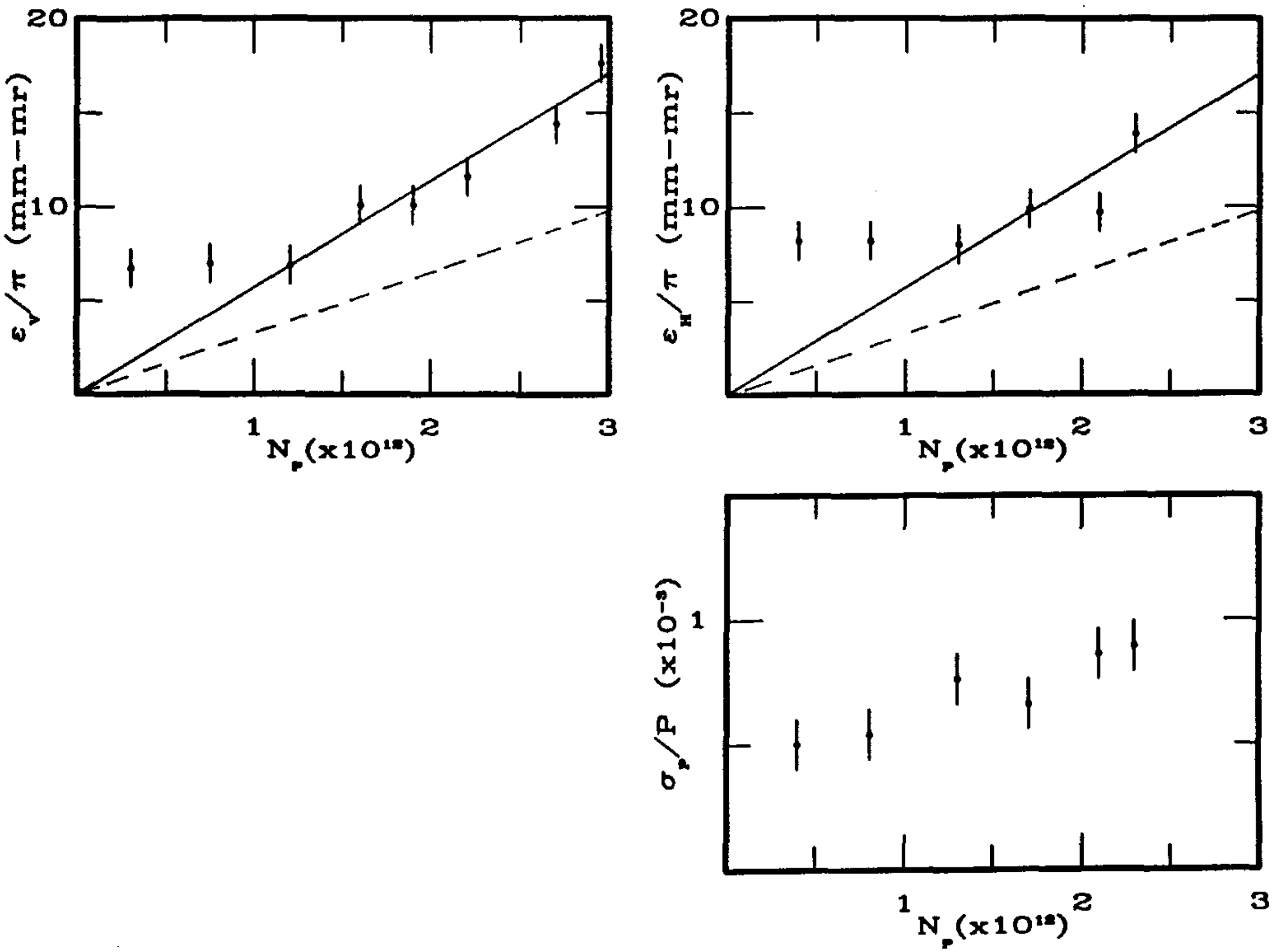
The Upgrade requires seven 10 MW, 805 MHz power supplies using a klystron output stage. A klystron with the required specifications can be developed from existing commercial klystrons but a development contract for the first prototype and a lead time of about one year would be required. We would plan to build a 10 MW prototype system at Fermilab so that the prototype klystron could be tested upon delivery. The specification of the final rf station would be derived from the operation of the prototype and it would serve as the source of spare components for the other stations after retrofit. The estimated cost for FY88 would be 800 K$ for the klystron and 400 K$ for the necessary driver systems.

The second area of major concern involves the low energy end of the Linac. It is well known that the phase-space dimensions of the H- beam are diluted by a factor of two or three from the ion source to the Linac, and by another factor of two in the Linac below 10 MeV. This phenomena is likely due to two effects; one, the influence of space charge forces within the beam, and second, the effect of the coupling between the longitudinal and transverse dimensions of the beams. Both effects have not been adequately measured or theoretically calculated. A set of on-line profile monitors and other diagnostics are being designed and will be installed to improve the measurements; also an off-line ion-source and transport test bench is being implemented to allow measurements to be made. A plasma lens has been designed and is being built to neutralize the beam and provide strong focussing of the beam as it emerges from the ion source extraction lens. Calculational programs are being developed to model particle motion as an aid in understanding the observed phase space dilution. With a better understanding of these phenomena it will be possible to design and construct a new system which will likely include an rf quadrupole (RFQ) and a new or modified Linac tank no. 1 with matching elements, thereby improving the beam emittance and system reliability.

Extensive modifications were carried out on the 8 GeV Booster during the 1986 summer shutdown. These changes were aimed at both improving the Booster performance and at upgrading diagnostics in order to foster further improvements which will enhance collider and fixed target operations. Major changes included: 1) elimination of the old Xerox 530 based controls system and replacement with a new system which integrated the Booster into the Accelerator Division controls network (ACNET); 2) installation of a new beam position monitoring (BPM) system; 3) rebuilding the low level RF system to improve performance and improve operational flexibility; 4) installation of a transition jump system; and 5) redesign and rebuilding of the "short sextupole" system. In addition a major improvement occurred during installation of the BPM system when a piece of epoxy was removed which was discovered to be partially obscuring the Booster aperture.

The Booster is presently capable of delivering $3x10^{12}$ protons per pulse; however the beam size is such that this beam will not fit into the Main Ring. For antiproton production we have been running about $2.0x10^{12}$ protons per pulse. Present Booster performance is summarized in the accompanying figure. Displayed are the transverse and longitudinal emittances delivered from the Booster as a function of delivered beam current. It is seen that for intensities below about $1.5x10^{12}$ the (invariant) transverse emittances are essentially independent of beam intensity, while they start rising at higher intensities. The momentum spread also is seen to rise with intensity. (For reference a momentum spread of 10^{-3} corresponds to a longitudinal emittance of about 0.35 eV-sec.). The dependence of transverse emittance on intensity is thought to be due to space charge forces at injection. The solid curves on the accompanying figure are the contours of fixed space-charge tune shift $\Delta\nu = 0.35$ at 200 MeV. Since the physical aperture of the Booster is presently about 20π this effect is presently limiting the total intensity deliverable from the Booster to about 3.0×10^{12}. Following the upgrades completed last summer, the increase in momentum spread with intensity is due almost entirely to a longitudinal coupled bunch instability.

We have expanded some effort on improving both the transverse and longitudinal performance of the Booster. Experimentation with the capture process has resulted in somewhat more favorable bunching factors at injection ameliorating the space-charge problem somewhat and we are presently looking at the use of sextupole resonance correction as a means of improving performance further. It appears unlikely that overall performance measured in terms of particles per unit transverse phase space can be improved by more than another 5-10% this way. Substantial improvement in this area is only possible through raising the injection energy to take advantage of the kinematic dependence of the space charge forces. A 400 MeV injection energy, as proposed, should improve the transverse density out of the Booster by a factor of about 1.7. The dashed curves on the accompanying figure show the position $\Delta\nu = 0.35$ contour at 400 MeV. We expect to be able to deliver 3×10^{12} protons with a 10π emittance following the Linac Upgrade. We have already made some progress on improving longitudinal emittance delivered from the Booster. Previously mentioned improvements to the low level RF system and the implementation of a transition jump system have nearly eliminated dilution up to and through transition. A longitudinal coupled bunch instability which grows after transition is presently causing the increase in momentum spread with intensity. During early April we installed mode dampers on all eighteen rf stations in order to combat this problem. This resulted in an immediate reduction of about 30% in the longitudinal emittance being delivered from the Booster at high intensity. We are also currently building a fast longitudinal damper and are contemplating installation of a higher harmonic (Landau) cavity for giving us further control over this problem.


ε_V/π (mm-mr)
20
10
1
2
3
$N_p(\times10^{12})$
ε_H/π (mm-mr)
20
10
1
2
3
$N_p(\times10^{12})$
σ_p/P ($\times10^{-3}$)
1
1
2
3
$N_p(\times10^{12})$

NEAR TERM AND LONG TERM PERFORMANCE IMPROVEMENTS

H. Edwards
May 1987

Now that the first collider run is successfully complete with an integrated luminosity of ~40 nb^{-1}, it is time to look toward programs of improvement that will increase the accelerator performance for not only the next collider run but for the next few years. The problem is that there are relatively few choices of parameters for improvement in the luminosity formula

$$\mathcal{L} \propto \frac{B N_{\bar{p}} N_p}{\beta^* \epsilon_N}$$

and one β^*, which is easy to improve, has already been exploited, even during this last run.

In the next collider run we hope to increase the integrated luminosity by approximately an order of magnitude to about 1/2 pb^{-1}. This will bring us to about the same level as CERN obtained per runprior to this year. However, with the ACOL upgrade CERN luminosity per run can be expected to double or triple over the next couple of years. They are hoping for an order of magnitude eventually. So not only do they have a head start of about 1.4 pb^{-1}, but it is likely that they will out perform us in the near future, albeit at lower energy, but with two detectors instead of just one.

It is clear that an agressive program is required here at Fermilab. The question is what is really achievable, not just pure optimism, P.R., or myth.

Upgrades are always dangerous. Tremendous effort and expense can be invested with little payoff. We are in a particularly vulnerable situation because we are still a factor of about 8 to 10 from the TeV I design goals, both for production and luminosity. It seems likely that some of the features of the upgrade will have to be used just to reach 10^{30}. As already mentioned, low-β less than 1 m has already been used this running period. Thus, at this time, after this long run, additional factors of 40 in production and 500 in luminosity from where we are now seem very difficult indeed.

We have however identified problem areas, know in many instances what should be done, and will begin to implement possible solutions as the discussion below will indicate.

A tenable approach is to put this in the perspective of trying to improve performance a factor of two with each yearly running period. If starting in 1988 we achieve $1/4\times10^{30}$ peak luminosity and $1/2(\text{pb})^{-1}$ integrated luminosity, then in 1992, five years from now, we would have a peak luminosity of 4×10^{30} (what CERN expects with ACOL) and a total integrated luminosity of $16(\text{pb})^{-1}$. Extending this to 1995 would give a peak luminosity of 32×10^{30}.

Table I gives approximate numbers of where we are now compared with TeV I design and the goals and parameter that we are trying to evaluate for the upgrade. Table II gives more details for the present operation and the goals for the next running period.

Note that though our antiproton bunch intensity $N\bar{p}$ is at present 1×10^{10}, it takes three times that number of antiprotons extracted from the Source because of inefficiencies in the transfers acceleration and bunch coalescing. With Source performance down a factor of 8 from TeV I design, it presently takes 7 hours of stacking to produce the required number of antiprotons. This is already comparable with the needed time for the upgrade, which does not take into account transmission inefficiencies.

At present it appears that the antiproton production cross section may be about a factor of three lower than expected. If this is true, then we will have to work even harder to meet the 10^{11}/hr stacking rate, let alone the 4×10^{11} rate.

With this rather pessimistic preamble, what are some of the potential gains we should be contemplating.

Source Production

1) Higher targeting rate. We will try this summer to develop acceleration of three Booster batches in the Main Ring with their sequential extraction to the Pbar Source target. The average targeting rate will then be just over 1/2 Hz (TeV I design). Long term, we hope to push this to 1 Hz average with six Booster batches being accelerated each Main Ring cycle.

One question here is whether phase space will become diluted during the sequential bunch rotation and extraction.

2) More protons on target. a) Now that the Main Ring is together and there are no plans in the near future to tear it apart, we have begun to work on finding aperture restrictions. During the summer this work will continue. Specific locations which may require larger aperture or different magnets will be identified so that these magnets can be designed and built. Possible changes to the

Main Ring lattice which would improve the aperture will be investigated. These changes might include better dispersion match or higher tune.
b) Booster work on the coupled bunch instability has already improved the momentum spread of beam supplied to the Main Ring. Continuing work in this area is expected to lead to further improvements in Main Ring transmission. c) Long term, the Linac upgrade construction project should improve intensity in the Main Ring by a factor of 1.7. Undoubtedly additional intensity related problems in the Booster and Main Ring will have to be solved in order to realize this factor.

3) Target and Lens. Long range, the pbar production target and lens will require work, in order to handle the additional beam heating and rep rate loads. Development will include beam sweeping systems that work on the μsec time scale. Tracking between the 120 GeV beam on target and the 8 GeV production beam optics will be required.

4) Source aperture. In the next year or two the Debuncher aperture will be enlarged in order to accept more of the produced antiprotons.

5) Cooling. Short term, there will be a need to double the cooling power of the transverse debuncher 2 to 4 GHz system in order to compensate for the enlarged aperture. R&D has begun on 4-8 GHz systems and the prototype will be used for the Accumulator core cooling, and will improve the emittance of the pbar beam supplied to the Main Ring.

Long term 4-8 GHz cooling systems will be required in the Debuncher for transverse and longitudinal cooling, and for the Accumulator longitudinal stacktail system because of the higher targeting rep rates and fluxes. R&D on 8-16 HGz systems will be started for the Accumulator transverse and longitudinal core cooling. How realistic this high frequency cooling is, has yet to be determined. Lattice changes to both the Debuncher and Accumulator will be required to accommodate the higher cooling rates and frequencies.

Collider Beam Quality and Efficiency

1) Transmission of pbars to low-β. This run has really brought home to us that we have to pay attention to every step and process in the transport of the pbar beam from the Accumulator to low-β in the Tevatron. The 10-20% do add up and this run they left us with 30% of the pbars, if we were lucky. It also became apparent that we had better get all of our diagnostics calibrated and understood or we will be trying to fix problems where none existed and ignoring others that really are there.

a) Accumulator to Main Ring. We will improve the transport line optics, especially reduce the β amplitude at specific points, so that the line is less sensitive to small steering changes and to reduce the spot size relative to the physical aperture.

b) Main Ring transmission will, hopefully, be improved by the aperture work described above. The injected pbar beam goes through a large amplitude oscillation at F11 in the Main Ring. We will try to relocate the injection kicker so that this extra 180-degree oscillation is eliminated. This may require substituting two normal Main Ring magnets for a double strength magnet to make room for the kicker near the point of injection.

c) Coalescences. Efficient beam coalescing still is a problem. In the near term, work will go on to reduce the rf voltage still further during the coalescing process. RF beam loading compensation will have to be improved. The advantages of coalescing at 40 GeV in the Main Ring instead of 120 GeV will be evaluated and the process attempted, if it appears there is a potential gain. Just doing the manipulation under different conditions may be instructive.

For the long term upgrade as presently envisioned with many bunches, antiprotons would not have to be coalesced in the Main Ring but would be bunched in the Accumulator. Protons will still need coalecing if we want small transverse emittance and 6×10^{10} per bunch. Probably three bunches coalescing to one will be sufficient instead of the present 9-11. The Linac upgrade will make high intensity proton bunches much easier to obtain and bunches of 10^{11} may be possible with present methods and emittances.

d) Transfer to the Tevatron and Acceleration. In the near term, we must understand why there is beam loss during the first 1000 turns in the Tevatron. This is probably due to different tunes associated with the injection orbit. Control of the tunes and/or chromaticity as the injection devices ramp may need to be implemented.

The sextupole moment of the superconducting magnets changes with time after the excitation has been reduced from 900 GeV to the injection level. Automatic compensation for this time dependence is required in order to speed up the time required for shot setup. In the long run, the high luminosities of the upgrade require efficient and short duration transfer times with fills taking place as often as every two hours. At the present time the shot setup itself typically takes four hours, clearly in conflict with fills every two hours.

Control of the chromaticity and tunes at injection and in the parabola is probably very important for control of the emittance growth of the antiprotons in the Tevatron. With the upgrade and separated beams this will become even more critical.

2) Emittance. In the near term, we need to understand just how and when the emittance growth takes place before either type, p or $\bar{p}$, beam reaches the Tevatron. In the Tevatron, we need to control the growth of the antiprotons; hopefully, through careful tune and chromaticity control.

Studies in the Main Ring can take place this summer during fixed target operation in order to see if small emittances from the Booster ($\sim 12\pi$) can be preserved through the Main Ring acceleration and coalescing process.

In the longer term, growth must be controlled or the Linac energy upgrade will not improve the final beam emittance.

The long term upgrade calls for a factor of 2 smaller emittance, and the Linac energy increase is a fundamental part of this. As the present high luminosity upgrade scheme also calls for acceleration and deceleration of the stored beam in the Tevatron every two hours to replenish a fraction of the pbars, this process must be done without beam loss or emittance dilutions. Study will be required to ascertain how realistic this proposal really is.

3) Lower β^*. A final lattice design must be devised for low-β at B0, D0 and possibly A0. The goal is to try to get about 1/4-m β^* with dispersion that is small enough to not increase the spot size at the crossing point. Small dispersion around the ring is also essential for the separated beam.

Complete solutions for β^* less than 1 meter are available for one interaction region, but still must be worked out in detail for two interaction regions, and no work has been done as yet for the possibility of three. This is not a trivial problem, especially as it interacts with the beam separator design. How good an overall scheme can be found, will have tremendous impact on the overall success of any improvement plan.

4) Separators. Development of beam separator schemes are essential for any significant luminosity increase in order to avoid large beam-beam tune shifts. Studies to determine the adequacy of the Tevatron aperture for separated beam will be undertaken immediately. As soon as possible a prototype separator design will be implemented in order to test beam behavior, and to get a first order impression of the difficulties we are up against. Tests will include tune and chromaticity control of each of the beams, sensitivity to beam separation distance, and to two-dimensional spiral separation or one-dimensional horizontal or vertical separation. We have a tremendous amount to learn in this area. Simulations and their comparison with real beam measurements need to get started as there were very pessimistic simulation results from the SSC pbar-p option study.

5) Bunches. The number of bunches one finally ends up with in the Tevatron Upgrade design is strongly dependent on the separator design, injection and abort kicker designs, and the availability of pbars. Below a certain pbar bunch intensity there is no point in increasing the number of bunches.

In the near term, we will start addressing the problems related with trying 6x6 operation, first without then with separators. We already know this will require modification of our present kickers.

It is likely that as more pbars become available, that we will slowly try increasing the number of bunches with intermediate steps at 12 or 24 bunches. This must be worked out with the detector people or done only as studies.

6) Kickers. The problem with kickers become more and more difficult as the number of bunches increase, and rise and fall times must get faster and faster. Even now we find we are very sensitive to ringing at the end of kicker pulses affecting bunches already in the Tevatron ring.

In the long term, if we are to replenish only a fraction of the pbars at a transfer, then we must develop shuttered kickers to be used with separated beams at injection.

If we do get to many bunch operation, then the abort problem will get much more difficult. One of the problems is that at present a considerable gap is required in the counter circulating beams to accommodate the simultaneous rise time of the kickers for both beams. This problem is enhanced because the kickers are a considerable distance from one another and no beam can be between them when they fire.

Summary of Near Term Plans

1) Three batch sequential targeting from Main Ring for pbar production.
2) Increased aperture of debuncher and increased cooling power.
3) 4-8 GHz cooling development (8-16 GHz lower priority).
4) Main Ring aperture improvements and modification.
5) Linac 800 MHz R&D.
6) Booster coupled bunch instability improvement.
7) Main Ring coalescing improvements and testing at 40 GeV.
8) Tevatron automatic control of injection and parabola chromaticity and tune.
9) D0 low-β optics-second priority, A0 low-β possibility.
10) Prototype separator design and beam studies associated with separated beams.
11) Development of hardware and software for 6×6 bunch operation.

TABLE I

	Present	TeV I	Upgrade
N_p (10^{10})	5	6	5-6
$N_{\bar{p}}$ (10^{10})	1	6	2 1/2-3
B	3	3	144
$BN_{\bar{p}}$ (10^{11})	0.3	1.8	36
α	1/3	1	1
ϵ_N/π	24-36	24	12
β^* (m)	2/3	1	1/2-1/4
L (10^{25})	0.072	0.72	1
$\mathcal{L}$ (10^{25})	0.1	1	67 (≡50)
$R_{\bar{p}}$ (10^{11}/hr)	0.12	1	4
Ts (hr)	7	2	10

The luminosity is proportional to the number of bunches of each beam, B, and the number of particles of each type, p, pbar, in a bunch, $N_{p,\bar{p}}$. It is inversely proportional to the beam transverse invariant emittance, ϵ_N (assumed here the same for protons and pbars), and to the interaction point lattice amplitude function β^*.

$$\mathcal{L} \propto \frac{BN_{\bar{p}}}{\beta^*}\,\frac{N_p}{\epsilon_N/\pi} \qquad\qquad BN_{\bar{p}} = \alpha\, R_{\bar{p}}\, \mathrm{Ts}$$

$BN_{\bar{p}}$ is the total number of pbars in a store, and must be less than equal to the number produced by the Source over the average store duration, where $R_{\bar{p}}$ is the rate accumulated per hour, Ts is the store duration, and α is the transmission efficiency factor from the Source to low-β.

COLLIDER GOALS FOR 88

	DESIGN (TEV I)	APR 87	GOAL 88
COLLIDER			
ENERGY (TeV)	0.8-1.0	0.9	0.9
NUMBER OF BUNCHES	3×3	3×3	3×3
P STORED/BUNCH (10^{10})	6	5	6
$\bar{P}$ STORED/BUNCH (10^{10})	6	1	3
95% EMITTANCE ($\pi 10^{-6}$ M)	24	25×35	20
β^* (M)	1	2/3	1/2
PEAK LUMINOSITY (10^{30} CM^{-2}SEC^{-1})	1	0.1	1/4
INTEGRATED LUMINOSITY/WEEK (NB^{-1})	-	10	33
/RUN (NB^{-1})	-	35	400
$\bar{P}$ PRODUCTION			
PROTON INTENSITY/BATCH (10^{12})	2	1.3	1.8
BOOSTER BATCH/CYCLE	1	1	3
MR TARGET CYCLES/HR	1800	1400	630
PROTONS ON TARGET/HR (10^{15})	3.6	1.8	3.4
$\bar{P}$ ACCUMULATION/HR (10^{10})	10	1.2	2.4
$\bar{P}$ TRANSMISSION TO LOW-β	-	0.35	0.5
AVERAGE MINIMUM STORAGE TIME REQUIRED FROM PRODUCTION RATE (HR)	2	7	7.5

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