# INITIAL OPERATION OF THE TEVATRON COLLIDER

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The Tevatron is now the highest energy proton synchrotron and the only accelerator made with superconducting magnets. Operating since 1983 as a fixed-target machine at energies up to 800 GeV, it has now been modified to operate as a 900 GeV antiproton-proton collider. This paper describes the initial operation of the machine in this mode. The new features of the Fermilab complex, including the antiproton source and the Main Ring injector with its two overpasses and new rf requirements, are discussed. Beam characteristics in the Tevatron (including lifetimes, emittances, luminosity, beam-beam tune shifts, backgrounds, and low beta complications), the coordination of the steps in the accelerator chain, and the commissioning history are also discussed. Finally, some plans for the improvement of the collider are presented.

## Introduction

A superconducting collider has been a dream for some time. The idea of magnets operating at full excitation for hours or days with a reasonable power bill is very appealing. It is very natural that the pioneering work of the CERN AA and SPS on antiproton-proton colliders be extended to the Tevatron.

I am very pleased to have the opportunity to describe the adventure of the Fermilab Tevatron Collider. I am proud to represent my very talented and dedicated colleagues, many of whom are now in the trenches, trying to perform one of the most difficult technological feats in the history of mankind.

Figure 1 is a schematic of the Fermilab accelerator complex. Some of the machines are in the same place they were when the lab was first built around 1970. That is not to say those machines are the same as they were then. There are now two preaccs which provide $H^-$ ions. The LINAC is the same, but there are plans to replace its last sections with higher frequency, higher energy cavities to provide the Booster with brighter beams. The 8 GeV Booster synchrotron has some new bells and whistles including a new closed orbit measuring system and a $\gamma_t$-jump system. The 8 GeV transfer line between the Booster and Main Ring was completely redesigned and rebuilt last year.

The Main Ring synchrotron is no longer the 500 GeV primary machine it was, but has become the 150 GeV injector to the superconducting Tevatron. The Main Ring also has the task of providing the 120 GeV protons which produce pbars for the pbar source. The Main Ring has suffered many indignities in the transformation to Collider physics at Fermilab. Two overpasses to accommodate experimental areas have made it one of the truly non-planar machines in the world. Last summer the vacuum chamber was modified at about 1000 places to reduce its longitudinal impedance, necessary for rf gymnastics needed for collider operation. And in all of its many tasks it has to operate in the stray fields of the Tevatron, barely 2 feet away.

## Antiproton Source

The antiproton source has the two really new machines at Fermilab since the last Accelerator Conference. These two triangular 8 GeV storage rings are the Debuncher (outer) and Accumulator of antiprotons. They were first operational about 1 1/2 years ago when the first pbar-p collisions took place at Fermilab. Included in the Source is the pbar production target area which contains the lithium lens and many high radiation environment devices. There is also a transfer line directly between the Booster and the Accumulator for 8 GeV proton test beams.

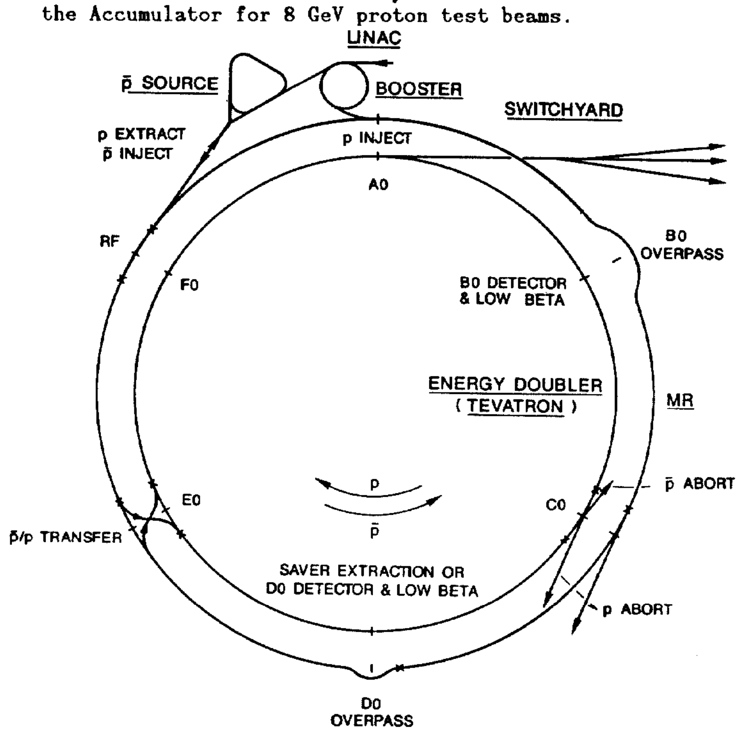


Figure 1. Schematic of the Fermilab accelerator complex. The Tevatron is 2 feet below the MR except in the overpass regions. Colliding beam operation and fixed target operation are expected to alternate every half year. Major detectors are at B0 and D0. The experiment at C0 shares the straight section with the MR and Tevatron abort systems, the one at E0 shares the straight sections with the MR to Tevatron p and pbar transfer systems. There is a low $\beta$ insert at B0. D0 will have one next year.

## Tevatron Modifications

The most notable improvement to the Tevatron in the last 6 months has been the increase in maximum energy from 800 to 900 Gev. Several superconducting magnets and cryogenic components were changed last year which allowed this upgrade. While 900 GeV collider operation has been reliable, it is not sure that fixed target operation with losses from high intensity resonant extraction will be possible at this higher energy.

## Some History

## The Tevatron as a Collider

In a certain sense, the collider operation of the Tevatron was something of an afterthought. When the Tevatron was designed, most thoughts were of the details of quench protection, magnet reproducibility, effects of beam losses, and a thousand other things other than how to use it as a collider. It is fortunate that while the Tevatron was being designed and built, people at CERN were developing the ideas and techniques needed for pbar-p colliders. In fact there has been a strong collaboration, especially in the business of pbar accumulation, between CERN and Fermilab and we are grateful for the help we have received.

## First Attempts in the Fall of 1985

By September of 1985 enough of the Antiproton Source had been completed that it seemed reasonable to try an engineering run to test the principles of the proposed collider. By mid-October a luminosity of some 1E24 was reached for a short while, terminating the run with high levels of euphoria and exhaustion. At that point, a very long and ambitious shutdown began.

## A Long Shutdown

Two of the six straight sections of the Tevatron are available for major experiments. Both of the areas had to be completely rebuilt for collider operation. The B0 area, with the Collider Detector at Fermilab (CDF), had to be rebuilt with an overpass of some 21 feet to allow the Main Ring beam to go over the detector. The D0 region required the complete construction of an experimental hall. Each of these projects required the replacement of a significant amount of the tunnel and the removal and replacement of many magnets of the Main Ring and Tevatron.

In the name of progress, several other projects also were done during the shutdown. These included a thousand modifications to the Main Ring vacuum chamber to reduce its impedance in order to prevent microwave instability, two new 8 GeV beam lines (Booster to MR and Booster to Debuncher), a new control system for the Booster, and the installation of smaller collider experiments at the C0 and E0 straight sections.

And so last fall, as the last wheelbarrows of debris were being removed from the tunnels, we began to discover the challenges of our newly reconditioned machines. This is part of the tale, of course, but the most interesting part of the story has to do with the new things that have been seen and how people are coping with a required increase of luminosity of 6 orders of magnitude.

## Problems, Solutions, and More Problems

Roughly speaking, the recovery from the long shutdown was the primary concern for September, October, and November '86. December was primarily for moving the CDF detector in place. Since January of this year, the emphasis has been to produce the highest possible luminosity for CDF. In fact, this is really a commissioning phase. New devices are put into operation as they become ready (last week saw the commissioning of the active transverse dampers in both the Main Ring and Tevatron). Changes are made in operating parameters as more is learned about pbar operation (tune adjustments up the ramp and during the low $\beta$ squeeze have been necessary to preserve the pbar emittance).

It is not really possible to do more than give a snapshot of the activity at Fermilab. Things are changing quickly. Yesterday's problems are left behind, today's problems are crises. In the spirit of entertainment, I will try to describe how things have been going for the last couple of weeks.

## Antiprotons

Eight GeV antiprotons are produced by 120 GeV protons striking a copper target. The pbars are focused by a lithium lens and injected into the Debuncher ring. RF bunch rotation is used to reduce the momentum spread of the pbars. Stochastic cooling is used to reduce the transverse emittance of the pbars in the 3 seconds prior to the next injection cycle. At the end of the 3 seconds the partially cooled pbars are transferred to the Accumulator ring where they are rf bunched and moved to the stack tail. Some 6 different stochastic cooling systems are used to create the familiar momentum profile while cooling the transverse emittances. The performance of the Antiproton Source will be covered in detail by Jack McCarthy and the performance of the stochastic cooling systems by John Marriner later this week.

Table I shows the present performance of the Source compared to the design and to the target goals for this run which is scheduled to end April 20. The largest problem is due to the paucity of pbars coming from the production target. There are apparently two independent reasons for the discrepancy between actual and design values. One is in the assumed production cross section. The other is in the pbar flux.

Table I, Pbar Source Stacking Rate

| stage | design report | feb 87 | missing factor feb 87 | goal 87 |
|---|---|---|---|---|
| MR intensity on target | 2E12 | 1.2E12 | 1.7 | 1.33 |
| pbars to Debuncher | 7E7 | 1.24E7 | 3.4 | 2.5 |
| pbars after bunch rotation | 7E7 | 1.03E7 | 1.2 | 1.1 |
| pbars into Accumulator | 7E7 | 0.86E7 | 1.2 | 1.1 |
| pbars on stacking orbit | 7E7 | 0.78E7 | 1.1 | 1.1 |
| pbars in core | 6E7 | 0.67E7 | 1.0 | 1.0 |
| cycles/hour | 1800 | 1200 | 1.5 | 1.5 |
| stacking rate | 10.8E10 | 0.8E10 | 13.5 | 6.7 |

Measurements using the production target, Cherenkov counter, collimators, and the Debuncher ring as a spectrometer show a cross section which is more than a factor of 2 lower than that assumed in the design report. The CERN AA had a similar experience with an entirely different kinematic region. There is not much to do about this particular missing factor.

Problems with the number of protons on target have to do with changes to the Main Ring over the past 7 years. When it was operating at 400 GeV for fixed target physics in 1980 it could accelerate over 2.5E12 protons per Booster batch. At present, the maximum intensity is half that much. It seems the admittance of the machine is greatly reduced in all 3 planes. This could be from the many new additions for beam transfers, especially septum magnets, and the new vertical dispersion caused by the overpasses.

Figure 2 shows the number of pbars in the accumulator over a one week period. Typically, the stacking rate is greater than 5E9/hour with a record of 8E9 pbars/hour. Also seen on the figure are the places where transfers to the collider have occurred. The fuzzy places just before the transfers are due to injected protons that are used to tune up the transfer lines. The most satisfying feature of the plot is that the number of pbars in the ring stayed above zero the entire week. The reliability of the Source has been quite good.

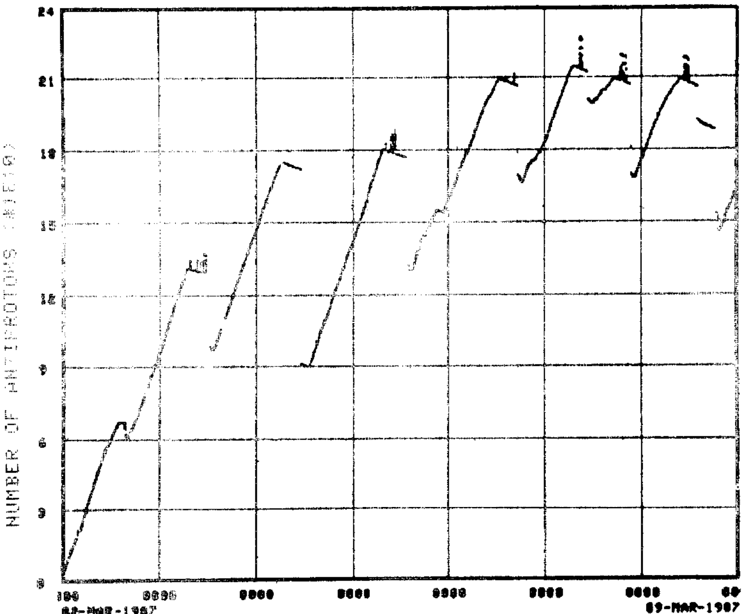


Figure 2. Plot of number of antiprotons stored in the Accumulator over a one week period. The ordinate is in units of 1.E10 particles. Stacking rates and Tevatron fills are clearly seen.

## Filling the Tevatron

### Coordination of Accelerator Systems

A subject near and dear to my heart is the control program used to synchronize all of the steps necessary to make colliding beams happen. The Sequencer runs as a primary application program on any of the console PDP-11 computers. Figure 3 is an image of the menu for the program and is here just to show the steps that must be performed.

A filling sequence really starts from the recovery from the last store. The *recover from low beta and *recover from store commands set all function generators and timers in the Tevatron to a cyclic ramping mode which is much like that used for fixed target operation. The ramp that is used is different from the fixed target ramp in two important respects. First, it has a much lower dE/dt because half the rf cavities are used for pbars and half for protons. Second, the ramp occurs only once per 2 minutes instead of once per minute. This lower duty factor seems to be a better match to the constant 150 GeV level that comes next so the refrigeration system is less likely to develop fluctuations when the ramp goes D.C.

Six ramps to 900 GeV are performed before the *set at 150/inject protons command is given. Six ramps is enough to verify that the beam can be accelerated and it also is enough to set up reasonable fields in the Tevatron magnets. The subject of time varying fields in superconducting magnets is discussed later.

After the Tevatron guide field is set at 150 GeV, any of the next 4 commands can be chosen. *test MR-Tev reverse injection causes beam to be transferred into the Tevatron where it coasts for 40 seconds before it is transferred back into the MR. This operation repeats every 2 minutes. This backward transfer tests the elements which will be used to inject the pbars into the Tevatron. This checkout and adjustment, if necessary, typically takes 20 minutes.

```
T48                 COLLIDING BEAM SEQUENCER
                              *log
*Help               3/13/87 15:01:22
→*set at 150/inject protns  3.551
 * store those protons
 *  test rev injectn Tev-MR
 *  test rev injectn MR-Acc
*set up pbar injection
* inject & store pbars
*ramp to flattop and store 3.316
*turn on low beta           10.83
* vary parameters
*recover from low beta
*recover from store         3.082
--------utilities---------
*adjust at 150 GeV
*freeze squeeze
*Kill Beam
*start VAX SDA
*unsqueeze
*hourly storage saves
*20 bunches
    Log Entry:
```

Figure 3. Control page for the Colliding Beam Sequencer. An interrupt while the cursor is below an asterisk causes the activity on that line to happen.

The *test MR-Acc reverse injection command can be made at any time, independent of the Tevatron energy. This command causes 8 GeV protons to be transferred from the MR into the Accumulator and is used to check out and adjust the elements needed for later pbar transfer. During this test procedure it is necessary to stop pbar accumulation. At present, the checkout and adjustment of the 8 GeV pbar elements typically take about 1.5 hours.

The *set up pbar injection is used to recover from the previous test steps by setting timer references and delays and setting up the proper ramps in the MR. After the preparations described above, the *inject and store pbars command causes the 3 pbar bunches (X, Y, and Z) to be transferred from the Accumulator to the MR to the Tevatron on successive 2 minute supercycles. On the fourth supercycle, the 3 proton bunches (A, B, and C) are transferred from the Booster to the MR to the Tevatron. Pbars are injected first because the pbar injection kickers in the Tevatron have tails on their waveforms which would disturb circulating protons.

After all 6 bunches have been injected, the *ramp to Flat Top and store command is used to accelerate the beam to 900 GeV where the Tevatron's function generators are again frozen and the store begins. The *turn on low beta command does all the manipulations of the 30 function generators needed to energize the low beta insertion at b0. Tunes, chromaticities, skew quad settings, and orbit adjustments can be made with the *vary parameters command.

### Main Ring Parameters

Eight or more rf bunches of beam must be combined to produce the intense bunch of protons or pbars needed for the collider. The process of combining the bunches is called coalescing and it is performed in the Main Ring at 150 GeV. The coalescing manipulations are the subject of a poster paper at this meeting.

Proton bunches of more than 5E10 have been produced; this compares well with the design value of 6E10.

## Beam in the Tevatron

### Time-varying Field Quality of Superconducting Magnets

One of the most surprising aspects of the conversion of the Tevatron from fixed target to colliding mode has been the variations in field quality of the Tevatron. The variations occur at 150 GeV and are functions of ramp history and time. Figure 4 shows a plot of $\langle b_2 \rangle$, the average sextupole component of the dipoles in the ring, versus time at 150 GeV. The $\langle b_2 \rangle$ values are inferred from beam measurements of chromaticity and there is a poster paper on the details. Changes in $\xi$ of more than 70 units have been seen over the course of several hours.

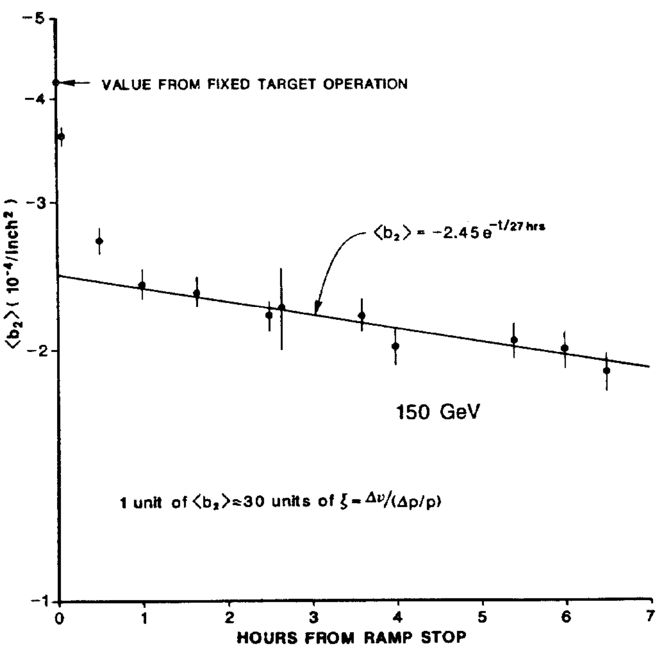


Figure 4. The change in the sextupole component of the Tevatron dipoles as a function of time at 150 GeV. The $\langle b_2 \rangle$ values are inferred from measured changes in chromaticity.

As can be imagined, this is a rather intriguing operational problem considering that we want to control $\xi$ to 2 ± 2 units. Going negative is a disaster as the head-tail instability quickly causes transverse emittance growth. A value of $\xi$ which is too large, combined with the ± 1E-3 $\Delta p/p$ of the coalesced bunches, leads to resonance overlap and transverse emittance growth as well. So far, the solution has been to have exactly 6 ramps to 900 GeV prior to the freeze at 150 GeV to establish the ramp history. Then, as time goes on, the *adjust at 150 command is used to reset the chromaticity correcting sextupoles in the ring according to the data of figure 4. This has worked pretty well, although the continuation from the 150 GeV level to the ramp is a bit tricky.

### Beam-Beam Effects Already

For proton bunch intensities of 4E10 the calculated antiproton beam-beam tune shift is .007. Since the proton bunch intensity is 2/3 of the design value, the beam-beam effects at this early time in the collider history are nearly as big as they will be. And we have started to see effects much as have been seen at the CERN SPS. We note that if the pbars have an rms emittance larger than the protons, the pbars will be lost until the emittances become the same. This loss can be faster or slower depending on how well low order resonances are avoided.

Figure 5 shows flying wire transverse profiles of the A and Y bunches at 900 GeV before and after the squeeze to low beta at B0. The gain of the antiproton scintillation counter has been increased so the profiles have equal amplitude even though there are about 3E10 protons and only about 1E9 pbars. The pbar profile is the outer one both before and after the squeeze. The difference between the antiproton and proton profiles is shaded. After the squeeze, which takes about 4 minutes, the pbar profile appears to have been changed. Namely the full width at half maximum is reduced. About 15% of the pbar beam has been lost from the machine. Tails or wings have developed, as well. In another 1.4 hours the pbar profile becomes indistinguishable from the proton profile.

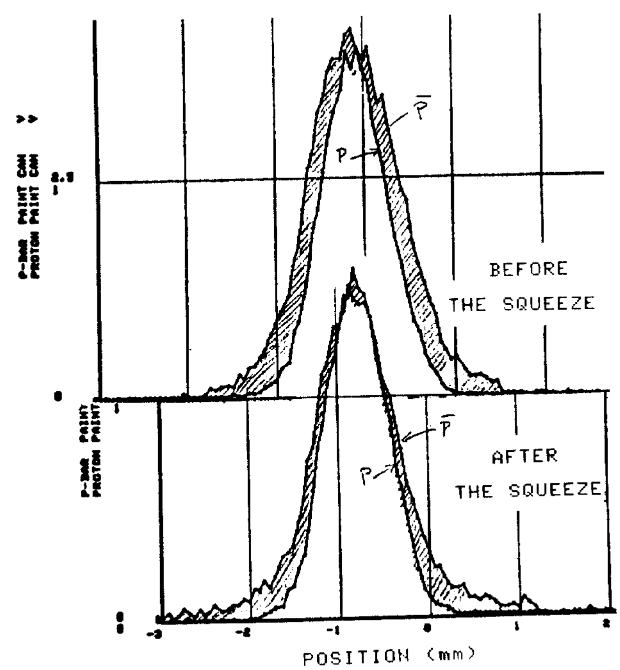


Figure 5. Vertical flying wire profiles of proton and antiproton bunches at 900 GeV before and after the low $\beta$ squeeze.

The squeeze at B0 is actually a series of 28 steps of the low beta quad circuits, each step an optical solution of the machine. Many other things step along with those quads, but that is another story. Because the superconducting quads are limited to about 200 amps/sec, the squeeze takes about 100 times as long as at CERN, and we have found that the tunes must be well controlled at each of the 28 steps. A slight shift into the region of the 5th order resonances during the squeeze has caused as much as 60% of the pbars to be lost from the machine.

### RF Highs and Lows

Both the high and low level rf systems have had to be redone for collider operation. The phase feedback systems for the individual proton and pbar bunches have recently been commissioned. Figure 6 shows the measured bunch lengths during a store in which the individual bunch feedback loops were working for the A and B bunches, but not for the C and X bunches. The intensity lifetimes for the bunches with feedback are about 100 hours.

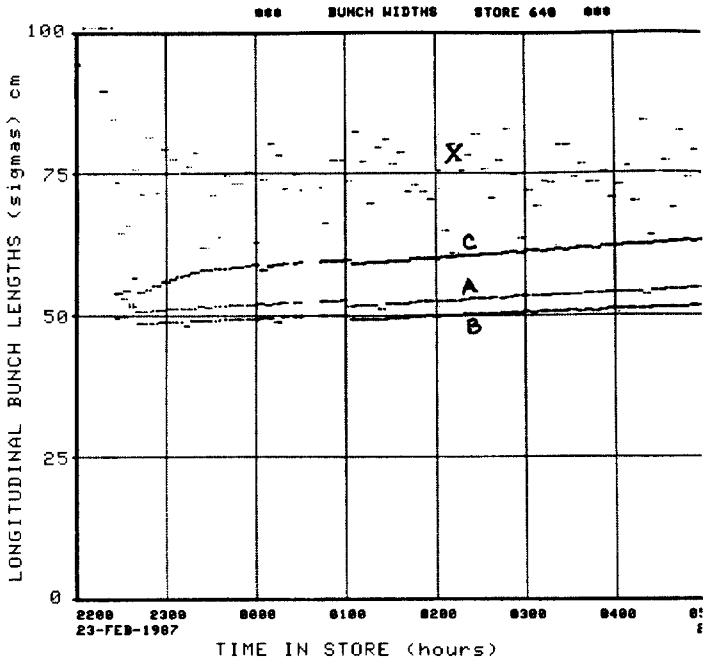


Figure 6. Bunch length growth at 900 GeV in the Tevatron. Bunches A and B have phase feedback; C and X do not.

## Present Limitations and the Future

### Luminosity and Luminosity Lifetime

Flying wire transverse profile monitors and sampled bunch longitudinal monitors have been used to estimate the luminosity during stores. Judging by the disagreement in the various methods of determining the bunch intensity, there is at least a possible error of 50% in the luminosity estimate. A conservative estimate of the peak luminosity as of March 12 is 1.2E28 $cm^{-2}s^{-1}$.

The luminosity can also be monitored by the CDF experiment using coincidence rates of scintillation counter hodoscopes on each side of the interaction region. Since the pbar-p cross section is not known and the triggering efficiency is also not well known, this luminosity monitor is only relative. Generally the luminosity lifetime starts near 12 hours and gradually increases to about 20 hours after 10 hours. At present, the luminosity lifetime is dominated by the growth of the transverse emittance of the beams. The growth rate seems to be much faster than one expects from intrabeam scattering. In fact, one can see strong horizontal betatron tune lines on the spectrum analyzer connected to any position detector. Perhaps we have a power supply ripple problem much like the one discovered and cured at the SPS.

Of course the real luminosity lifetime can be dominated by unscheduled interruptions. We still have them, but the number of stores which have been terminated on purpose is increasing. There has been a store of 28 hours, and the average length of a store has increased from 2 hours to over 10 hours since the beginning of the year.

The following table summarizes the present state of the Collider. Also shown are the goals for the present run and the ultimate goals of the design report.

### Tevatron Collider Achievements and Goals

| | mid March'87 | Goals Spring'87 | Design |
|---|---|---|---|
| **Antiprotons** | | | |
| From Accumulator/bunch | 1.8E10 | 2.7E10 | |
| MR transmission | .60 | .75 | |
| Coalescing Efficiency | .5-.75 | .5 | |
| Transmission MR to low $\beta$ | .80 | 1.0 | |
| Overall transmission | .12-.25 | .37 | |
| number stored/bunch | 0.3E10 | 1E10 | 6E10 |
| Accumulation rate/hr | 0.8E10 | 1.5E10 | 11E10 |
| **Protons** | | | |
| Extracted from Booster | 1.5E11 | | |
| MR transmission | .56 | .75 | |
| coalescing efficiency | .53 | .50 | |
| transmission MR to low $\beta$ | .8 | 1.0 | |
| overall transmission | .24 | .37 | |
| number stored/bunch | 3E10 | 4E10 | 6E10 |
| **Collisions** | | | |
| number of bunches | 3X3 | 3X3 | 3X3 |
| transverse emittance | 25 p | 24 | 24 |
| (95% normalized) | 35 pbar | 24 | 24 |
| Peak luminosity | 1.2E28 | 1E29 | 1E30 |

## Conclusions

There are many problems to be solved. The pbar stacking rate in the Accumulator needs to be more than an order of magnitude better. This can be improved by accelerating multiple Booster batches in the MR and thereby improving the effective cycle rate of the MR. The MR intensity needs to be increased. The Accumulator has a problem with maintaining a large stacking rate when the stack core gets large. Some improvements in the stochastic cooling hardware may be needed.

The Main Ring efficiency for accelerating antiprotons needs improvement. Bunch coalescing efficiency is also lower than one expects. In the Tevatron, better control of tune and chromaticity is needed to avoid transverse emittance growth of the pbar beams, especially in the presence of the beam-beam interaction.

The mechanisms for beam transfers and stores are working pretty well. The operations crew now handles all the transfer details including testing the reverse injection lines. The most difficult part of the transfers is to gather the diagnostic data needed for improving the transfer efficiency.

Every day there is evidence of increased understanding and improved performance. There is every reason to believe that the next 2 orders of magnitude in luminosity will come in good time.

## Acknowledgments


I hope I've made it clear that I have been describing the work of a few hundred people. I thank them for this opportunity to be their representative.